

Absorption of Stopped Negative Pions in the Heavy Nuclei
 ^{165}Ho , ^{181}Ta , ^{197}Au , $^{\text{nat}}\text{Ti}$, $^{\text{nat}}\text{Pb}$, ^{209}Bi , ^{238}U and the
Nickel Isotopes ^{58}Ni , ^{60}Ni , ^{62}Ni , ^{64}Ni

INAUGURAL-DISSERTATION

zur
Erlangung der philosophischen Doktorwürde
vorgelegt der
Philosophischen Fakultät II
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UNIVERSITÄT ZÜRICH

von

Hanspeter ISAAK
aus Ettiswil (LU)

Begutachtet von Herrn Prof. Dr. R. Engfer



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Characterization of Organic Negative Polymers in the Heavy Metal
Catalyzed Polymerization of α -Cyanoacrylates and the
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ANALYTICAL INVESTIGATION

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ABSTRACT.

The spectra of neutrons emitted after the absorption of stopped negative pions in selected heavy nuclei from ^{165}Ho to ^{238}U and the spectra of neutrons and charged particles emitted after the absorption of stopped negative pions in Ni isotopes have been measured and interpreted in terms of models for pion absorption on a peripheral nucleon pair and subsequent secondary reactions. The ratios R of absorbing np to pp pairs in the nucleus were found to be close to the statistical ratio for ^{197}Au and significantly lower for the Ni isotopes. The contribution from pion absorption on heavier clusters has been estimated to be at most about 25% for the nuclei investigated. The extracted nuclear temperature parameters for heavy nuclei demonstrate the lack of shell effects in the nuclear level density parameter in the compound nuclear excitation region sampled by the stopped pion reaction. For ^{238}U the ratio of pre- to post-fission neutrons has been estimated from the experimental data.

ABSORPTION OF STOPPED NEGATIVE PIONS IN THE HEAVY NUCLEI ^{165}Ho , ^{181}Ta , ^{197}Au , $^{\text{nat}}\text{Tl}$, $^{\text{nat}}\text{Pb}$, ^{209}Bi , ^{238}U AND THE NICKEL ISOTOPES ^{58}Ni , ^{60}Ni , ^{62}Ni , ^{64}Ni .

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1. INTRODUCTION.

The spectra of the neutrons emitted in the kinematic region of the stopped pion reaction ($E \leq m_{\pi} \cdot c^2$) contain [i] fast neutrons produced in the primary process of pion absorption, that manage to escape without much further nuclear interaction; [ii] intermediate energy neutrons, emitted as a result of secondary nuclear reactions induced by the fast nucleonic cascade, before the nucleus reaches equilibrium; and [iii] low energy neutrons, evaporated by the daughter nuclei produced after nuclear equilibration. The primary neutrons are expected to yield characteristics of the pion absorption mechanism itself (section 1.1.); the pre-equilibrium neutrons should provide insight into the complex nucleonic cascade (section 1.1.); finally, the evaporation neutrons should give information on the nuclear evaporation parameters at the relatively high excitation energies (~ 70 MeV) sampled by the stopped pion reaction (section 1.2.). The present experiment fulfills all three expectations quite nicely.

Spectroscopy of neutrons emitted after the absorption of stopped negative pions in the heavy nuclei ^{165}Ho , ^{181}Ta , ^{197}Au , natTl , natPb , ^{209}Bi and ^{238}U was performed in order to obtain information on nuclear structure and the dependence of the neutron yields on target mass number. Previous experiments [AndH64], [VenF64], [HatM65] measuring neutrons after the absorption of stopped negative pions in heavy nuclei show large discrepancies in their results and do not allow any reliable extraction of the nuclear level density parameter from the experimental data. Therefore in the present experiment a series of technical improvements have been introduced together with a careful study of the separation of evaporation from primary and pre-equilibrium neutron emission. In a simple analysis of the experimental data the nuclear evaporation model of Weisskopf [Weis37] and LeCouteur and Lang [LeCo52], [LeCL59] was applied to the neutron spectra, thus allowing the study of statistical nuclear structure aspects of the target nuclei such as

nuclear temperature and level density. Nuclei around the magic nucleus ^{208}Pb were chosen in order to see whether or not the strong nuclear shell effects observed for low excitation energies are also present at higher energies, as suggested by the data of Venuti et al. [VenF64]. Spectroscopy of neutrons and charged particles emitted after the absorption of stopped negative pions in the Ni isotopes ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni was performed in order to study the dependence of the neutron and charged particle yields on neutron number. Other questions of interest, related to the pion absorption process itself, namely the ratio R of absorbing np to pp pairs in the nucleus and the importance of pion absorption on heavier clusters are also discussed. Finally, results from stopped π^- -induced reactions are compared with p - and α -induced reactions at similar excitation energies.

1.1. ABSORPTION OF STOPPED NEGATIVE PIONS IN NUCLEI.

The complex process of absorption of stopped negative pions in nuclei starts with the electromagnetic atomic capture [FerT47] of the negative pion into an excited Bohr orbit. Under the emission of X-rays and Auger electrons the pion then cascades down to lower orbits and is immediately absorbed by the nucleus by the strong interaction if the orbit has some overlap with the nucleus. Absorption of stopped negative pions in nuclei is especially suitable for the study of nuclear structure [Mars52], [Eric62], [Eric74] because negative pions are captured at rest from low lying atomic orbitals, transfer very little momentum and release a large amount of energy, their rest energy of about 140 MeV, to the nucleus. The entire nuclear absorption of stopped negative pions may be divided into three steps:

1.] In the primary absorption process the negative pion is absorbed by a cluster of two or more nucleons in the nucleus, the total energy of the pion being converted into kinetic energy of the nucleons in the primary cluster.

2.] Primary nucleons leave the nucleus either directly without further nuclear interaction or after one or more collisions in the nucleus, so-called final state interactions. Both scattered primary nucleons and struck nucleons are called secondary or pre-equilibrium nucleons.

3.] After the emission of primary and secondary nucleons, often called direct or non-evaporation nucleons, the nucleus is usually in an excited state and emits evaporation nucleons and γ -rays. Finally, if the remaining nucleus is unstable it decays by β -emission or electron capture.

Of course the above mentioned division is artificial. Primary nucleons cannot be experimentally separated unambiguously from secondary nucleons. However, within the context of the nuclear evaporation model described in section 1.2., evaporation nucleons can be separated from the non-evaporation nucleons by their energy distribution. This separation allows statistical nuclear structure aspects of the target nuclei to be studied. Of the original 140 MeV deposited by the pion, about 70 MeV (see section 3.1.) is carried away by the direct nucleons and the rest, 70 MeV, is the excitation energy of the remaining nucleus.

PRIMARY ABSORPTION PROCESS. In the present literature two mechanisms for the primary absorption process have been discussed:

1.] In the two nucleon absorption model the stopped negative pion is absorbed by two nucleons in the nucleus. This model is often called the "quasi-deuteron" model.

2.] In the multi nucleon absorption model the stopped negative pion is absorbed by a heavier cluster of mainly four nucleons in the nucleus. This model is often called the "quasi-alpha" model.

Absorption of stopped negative pions on a single nucleon in the nucleus as suggested by Tamor [Tamo50] is kinematically suppressed and is therefore an unlikely absorption mode [LeTo66]. Energy and momentum conservation for the single nucleon absorption process

$$\pi^- "p" \rightarrow n \quad \text{single nucleon absorption (1.1)}$$

require a momentum for the absorbing proton P_p at the instant of absorption of $P_p = \sqrt{2m \cdot (m_\pi - B)} \sim 500 \text{ MeV/c}$, where m is the neutron mass, m_π the pion mass and B the proton binding energy in the nucleus. This is far beyond the Fermi momentum of nucleons in the nucleus of about 250 MeV/c .

In the two nucleon model first introduced by Brueckner, Serber and Watson [BruS51] there are two possibilities for pion absorption, namely the absorption on an np or a pp pair in the nucleus:

$$\pi^- "np" \rightarrow nn \quad \text{Two nucleon absorption on an } np \text{ pair (1.2)}$$

$$\pi^- "pp" \rightarrow np \quad \text{Two nucleon absorption on a } pp \text{ pair (1.3)}$$

In both cases the two nucleons are emitted back to back and have an initial kinetic energy of about half the pion rest mass. For statistically distributed protons and neutrons one expects the following absorption probabilities w_{np} and w_{pp} for absorption on an np or a pp pair in the nucleus

$$w_{np} \approx N \cdot Z \text{ and } w_{pp} \approx Z \cdot (Z-1)/2 \quad (1.4)$$

yielding the statistical ratio R' of absorbing np to pp pairs in the nucleus

$$R' = 2N/(Z-1), \quad \text{statistical ratio (1.5)}$$

with N and Z the neutron and atomic numbers of the target nuclei. In general, a stopped negative pion can be absorbed

not only by two nucleons but also by other multi nucleon clusters as for example ^3He -, ^4He - or ^6Li -clusters in the nucleus. In the case of absorption of stopped negative pions on a "quasi-alpha" there are three main channels:

$\pi^- \text{ } ^4\text{He} \rightarrow \text{tn}$ Quasi-alpha absorption, t-channel (1.6)
 $\pi^- \text{ } ^4\text{He} \rightarrow \text{dnn}$ Quasi-alpha absorption, d-channel (1.7)
 $\pi^- \text{ } ^4\text{He} \rightarrow \text{pnnn}$ Quasi-alpha absorption, p-channel. (1.8)

The relative probabilities for the corresponding reactions for the absorption of stopped negative pions on a ^4He nucleus are $(19 \pm 1)\%$, $(58 \pm 7)\%$ and $(26 \pm 6)\%$ [BloK63], [CalC69] respectively.

FINAL STATE INTERACTIONS. At present it seems that both the two and four nucleon absorption mechanisms contribute to the pion absorption process. Neutrons and protons emitted after the absorption of stopped negative pions in nuclei, however, come predominantly from the absorption on a nucleon pair. The large triton yields found in experiments [SchH61], [BloK63], [ZioC70], [CasC71], [BudZ72], [LeeM72], [PruE81] have often been interpreted as an indication for pion absorption on four nucleons [Koly66]. More recent calculations postulate final state interactions to explain the large triton yields, retaining the assumption that the pion is absorbed on a nucleon pair [IljN76], [KozZ80], [ChiH81]. The following models all consider the nucleus as a Fermi gas of free nucleons and assume the pion to be absorbed on a nucleon pair in the nucleus. Iljinov et al. [IljN76], Mukhopadhyay et al. [MukH79] and Kozlowski and Zglinski [KozZ80] assume a statistical ratio R' of absorbing $n\bar{p}$ to $p\bar{p}$ pairs in the nucleus and Gadioli and Gadioli-Erba take $R = 4$, whereas Chiang and Huefner need a much larger ratio R .

The geometrical models of Mukhopadhyay et al. [MukH79] and Chiang and Huefner [ChiH81] treat only the

direct stage of the stopped pion reaction. In their geometrical model Mukhopadhyay et al. [MukH79] assume that one of the two primary nucleons leaves the nucleus, while the other is absorbed, producing a compound nucleus with a known excitation energy. In this model secondary nucleons are neglected completely. Nevertheless, the prediction for the direct neutron spectrum agrees quite well with the high energy part of the measured spectrum [IsaZ80]. However, the shape of the experimental neutron spectrum between 40 and 80 MeV is somewhat flatter, and a pre-equilibrium contribution below 40 MeV is seen.

Better overall agreement with the neutron and charged particle experiments is obtained with the geometrical model of Chiang and Huefner [ChiH81]. In this model secondary reactions are taken into account in the following manner: the events of the intranuclear cascade are ordered according to the number of inelastic collisions of nucleons in the nucleus. This ordering corresponds to the following ordering in the experimental spectra: primary nucleons dominate the high energy part of the spectra. For lower energies those secondary nucleons with one interaction in the intranuclear cascade are most important. For still lower energies the nucleons from two interactions are to be found and so on. Finally at the low energy end of the spectrum the evaporation nucleons dominate. Precompound reactions with nucleons with energies between 15 and 100 MeV [ChiH80] show a rapid convergence of the intranuclear cascade, so that the experimental spectra are quite well described by a sum of contributions from single and double scattering plus evaporation. To correctly reproduce the absolute magnitude of emitted protons, a ratio R of absorbing np to pp pairs of 13 ± 6 for ^{12}C is needed in this model. This may be compared with the microscopic calculations of Shimizu and Faessler [ShiF78], [ShiF80] for ^{16}O , which predict values of R between 8.5 and 15 depending on the approximations used. The geometrical model of Chiang and Huefner predicts angular distributions, which agree quite well with the experiment.

In contrast to the geometrical models described above, the models of Iljinov et al. [IljN76], Gadioli and Gadioli-Erba [GadG76] and Kozlowski and Zglinski [KozZ80] incorporate a treatment of both the non-equilibrium and the equilibrium phases of the stopped pion reaction. In the model of Kozlowski and Zglinski [KozZ80] the available excitation energy is distributed statistically among the four initial excitons in the finite Fermi potential well. The pre-equilibrium decay of the nucleus and the resultant compound nucleus distributions are then calculated using the method described in [KozZ78]. The agreement between theory and experiment is good over the entire energy region from 2 to 130 MeV. As will be shown in section 3.3., the spectra of neutrons emitted after the absorption of stopped negative pions in heavy nuclei are consistent with the two nucleon absorption model, the contribution from pion absorption on heavier clusters being at most about 25%. Information on the ratio R of absorbing np to pp pairs in the nucleus has also been extracted from the neutron and charged particle spectra. The above mentioned calculations of the intranuclear cascade [IljN76], [GadG76], [KozZ80], assuming pion absorption on a peripheral nucleon pair and ratios R around the statistical ratio R' all reproduce the neutron data quite well. A comparison of measured spectra of neutrons and charged particles emitted after the absorption of stopped negative pions in ^{197}Au with different calculations [IljN76], [GadG76], [KozZ80], [ChiH81] is given in Fig.14 of section 3.1..

EXPERIMENTAL SITUATION. To investigate the entire reaction mechanism following the nuclear absorption of stopped negative pions, different experimental techniques have been used:

1.] Emulsion, cloud and bubble chamber studies [Mars52] and references cited therein, [TonE52], [TurN53], [Wins53], [TurF53], [SchH61] to obtain neutron and charged particle multiplicities;

2.] In-beam γ -ray spectroscopy and activation analysis [LewU73], [JacM73], [EbeA75], [CasJ77], [JacK78], [BeeB78], [PruE79] to obtain the the yields of residual nuclei;

3.] Neutron spectroscopy [AndH64], [VenF64], [HatM65], [HarI78], [BasE79], [KleB79], [IsaZ80], [EngH80],

4.] Neutron-neutron angular correlations [OzaW60], [DavM66], [NorK68], [CalC69], [CheS69], [CheS70], [BasE76], [BasK77], [HarI78] and

5.] Neutron-charged particle angular correlations [OzaW60], [NorK68], [LeeM72], [BarM73], [HeuE80] to obtain information on the primary absorption process, mainly on the quasi-deuteron absorption with the important ratio R of absorbing np to pp pairs in the nucleus;

6.] Charged particle spectroscopy [CohK65], [MinC69], [ZioC70], [CasC71], [BudZ72], [ComM75], [SchC79], [Meye79], [MecB79], [PruE81], [Senn81] and

7.] Charged particle-charged particle angular correlations [Walt77], [SenF81], [Senn81] to study the ratio R and the importance of pion absorption on heavier clusters and of final state interactions, such as knock-on and pick-up reactions following the primary absorption process.

Experimental and theoretical aspects of pion interactions with nuclei are reviewed by Koltun [Kolt69], Kopaleishvilli [Kopa71], Huefner [Huef75] and Walter [Walt77].

1.2. NUCLEAR TEMPERATURES FROM NEUTRON SPECTROSCOPY AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN NUCLEI.

Earlier measurements of neutrons emitted after the absorption of stopped negative pions in nuclei [AndH64], [VenF64], [HatM65], [HarI78], [KleB79] show large discrepancies in fitted values of the nuclear temperature parameters, neutron multiplicities and mean energies. From the point of view of nuclear shell effects, in the interesting region around ^{208}Pb , the nuclear temperatures differ by up to a factor of two from experiment to experiment ($\theta = 1.7$ MeV [AndH64], 3.4 MeV [VenF64] and 2.7 MeV [HatM65] for ^{nat}Pb). These large discrepancies in the earlier experimental data did not allow any reliable extraction of the level density parameter as a function of target mass to be made. A comparison of results for single neutron spectroscopy after the absorption of stopped negative pions in nuclei [AndH64], [VenF65], [HatM65], [Isaa76], [HarI78], [KleB79], [this work] is given in Fig.25a-c and Tab.8a of the appendix.

One of the principal results of the present measurements of neutrons emitted after the absorption of stopped negative pions in several heavy nuclei from ^{165}Ho to ^{238}U is the lack of nuclear shell effects in the level density parameters in the region around the magic nucleus ^{208}Pb . For a better understanding of the connections between the nuclear temperature parameters, neutron multiplicities and mean neutron energies, which can be extracted from the neutron spectra, and the nuclear level density parameter, a short description of the statistical theory of neutron evaporation is given below. It basically follows the treatment by Weisskopf [Weis37] for single neutron emission, with the modification of LeCouteur and Lang [LeCo52], [LeCL59] to include successive neutron emission.

Negative pion induced reactions in ^{58}Ni , ^{60}Ni and ^{62}Ni [CasJ77] for pions with a kinetic energy of 0, 45 and 220 MeV indicate that the nucleon multiplicities are

insensitive to the incident pion energy and that the mean number of emitted neutrons increases strongly with increasing neutron number, whereas the mean number of emitted protons remains constant. This asymmetry between neutron and proton emission cannot be understood from simple binding energy considerations, which would predict the sum of emitted neutrons and protons to be roughly constant. p-induced reactions at 136 MeV in ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni [SadJ77] show that the average number of emitted nucleons is independent of target isospin. To resolve this contradiction between π^- - and p-induced reactions, neutron and charged particle spectroscopy after the absorption of stopped negative pions in Ni isotopes were performed.

THEORY OF NEUTRON EVAPORATION. Provided the energies involved are large in comparison with the lowest excitation energies of the nuclei, statistical methods may be applied to the calculation of nuclear processes. Weisskopf [Weis37] derived a general statistical formula for the emission of particles by highly excited heavy nuclei and showed that the disintegration of the compound nucleus can be described as an evaporation process. The expression contains several nuclear structure parameters, the most important being the level density as a function of excitation energy. In the following only neutron emission will be discussed. Charged particle emission is treated in [Weis37]. The probability per unit time $w_{fi}(E)dE$ for the emission of a neutron with a kinetic energy E from a highly excited initial compound nucleus (A_i, U_i) , leading to a final residual nucleus (A_f, U_f) , with mass numbers A_i , A_f and excitation energies U_i, U_f respectively, is given by the expression [Weis37]:

$$w_{fi}(E)dE = c \cdot \sigma_{fi}(E) \cdot E \cdot (\rho_f(U_f)/\rho_i(U_i))dE, \quad (1.9)$$

where $c = 2\pi/(\pi^2 \cdot \hbar^3)$ is a constant characteristic of the emitted particle considered, m the particle mass, σ_{fi} the mean cross section for the inverse reaction, the capture of the neutron of energy E by the residual nucleus (A_f, U_f) and

$\rho_i(U_i)$, $\rho_f(U_f)$ the level densities of the initial and final nuclei at their respective excitation energies U_i and U_f . The excitation energy U_f of the residual nucleus is given by

$$U_f = U_i - B_i - E, \quad \text{excitation energy (1.10)}$$

B_i being the binding energy of the neutron when bound to the initial nucleus (A_i, U_i).

The substitution of the nuclear entropy $S(U)$ defined as

$$S(U) = \ln \rho(U) \quad \text{nuclear entropy (1.11)}$$

leads to

$$w_{fi}(E) dE = c \cdot \sigma_{fi}(E) \cdot E \cdot \exp(S_f(U_f) - S_i(U_i)), \quad (1.12)$$

where $S_i(U)$ and $S_f(U)$ are the nuclear entropy of the initial and final nuclei as a function of excitation energy, at their respective excitation energies U_i and U_f . Under the assumption that the energy E of the emitted neutron is small compared to $U_i - B_i$ (for stopped negative pion absorption in ^{197}Au : $\langle E \rangle = 2.1$ MeV and $U_i - B_i = 57$ MeV), the following expansion of the nuclear entropy is valid

$$S_f(U_f) = S_f(U_i - B_i) - E \cdot \frac{dS}{dU}(U) \Big|_{U=U_i-B_i} \quad (1.13)$$

Defining the nuclear temperature $\tau(U)$ by

$$\frac{dS}{dU}(U) = \frac{1}{\tau(U)} \quad \text{nuclear temperature (1.14)}$$

and setting $dN/dE(E) = w_{fi}(E)$ one obtains the following form for the neutron spectrum:

$$dN/dE(E) = Y(E) \cdot E \cdot \exp(-E/\tau_f(U_i - B_i)) \quad (1.15)$$

$$Y(E) = c \cdot \sigma_{fi}(E) \cdot \exp(S_f(U_i - B_i) - S_i(U_i)). \quad (1.16)$$

In general $\sigma_{fi}(E)$ does not depend appreciably on energy so

that Y may be treated as a constant. The nuclear temperature $\tau_f (U_i - B_i)$ hereafter simply called τ , is by no means the temperature of the evaporating compound nucleus. On the liberation of the neutron considerable cooling down takes place; the energy distribution of the evaporated neutrons corresponds to the temperature of the remaining nucleus.

Eq.(1.15) is correct for the case that one neutron is emitted. If the excitation energy U_i of the initial nucleus (A_i, U_i) is high enough, several neutrons may be emitted in succession and Eq.(1.15) no longer applies because after the first neutron emission, the nucleus has lost such a large amount of energy that a lower nuclear temperature must be ascribed to the remaining nucleus. LeCouteur and Lang [LeCo52], [LeCL59] showed that in this case Eq.(1.15) must be replaced by

$$dN/dE(E) = Y(E) \cdot E^{(1-1)} \cdot \exp(-E/\theta) \quad (1.17)$$

$$Y(E) = (\sigma_{fi}(E)/\sigma_0) \cdot (U_i - 0.5 B_i) / (B_i + \langle E \rangle') \cdot (1/\Gamma(1) \cdot \theta^1), \quad (1.18)$$

where σ_0 is the average of σ_{fi} over energy E , $\langle E \rangle'$ the mean neutron energy

$$\langle E \rangle' = 1 \cdot \theta \quad \text{mean energy} \quad (1.19)$$

and θ is an effective nuclear temperature parameter related to the nuclear temperature τ characteristic of the first neutron emission. The assumption of a nuclear entropy $S(U)$ of the form [Weis37], [CheH68]

$$S(U) = 2 \sqrt{(a \cdot U)} + \text{const}, \quad \text{nuclear entropy} \quad (1.20)$$

where the constant a is the level density parameter, leads to the following relation between excitation energy and nuclear temperature:

$$U = a \cdot \tau^2 \quad (1.21)$$

With the above power law one obtains for the parameters 1

and θ of Eq.(1.17) [LeCL59]:

$$l=16/11 \text{ and} \quad (1.22)$$

$$\theta = 11/12 \cdot \tau. \quad \text{effective nuclear temperature} \quad (1.23)$$

Thus from the measured nuclear temperatures θ the nuclear level density parameters a can be obtained if the excitation energy of the residual nucleus is known. For the absorption of stopped negative pions in nuclei the excitation energy can be estimated from the mean kinetic energies and multiplicities of the directly emitted particles. Eq.(1.21) then provides an interesting connection between the low energy part of the neutron spectra (needed for the determination of θ), the high energy part of the neutron and charged particle spectra (giving the mean excitation energy $\langle U \rangle$) and the level density parameter at the corresponding excitation energy.

2. EXPERIMENT AND ANALYSIS.

2.1. MECHANICAL SET-UP AND ELECTRONICS FOR NEUTRON SPECTROSCOPY.

2.1.1. MECHANICAL SET-UP FOR NEUTRON SPECTROSCOPY.

PION BEAM TELESCOPE. The experiments were performed at the vertical SIN π E3 pion beam line. Negative pions with a momentum of 110 MeV/c were monitored with a conventional fast counter telescope, consisting of four plastic scintillators S1, S2, S3 and S4, moderated in a polyethylene degrader and brought to rest in the target. The dimensions of the pion beam telescope with target and degrader are indicated in Fig.1. The beam spread at the site of the target was about 2.5 cm X 3.5 cm FWHM. The average pion flux during the measurements was about $4 \cdot 10^6 \pi/s$ for a proton current of 30 μ A. The rate of stopped pions in the target was determined by a 1234 signal from the pion beam telescope and was used for relative normalization. For neutron spectroscopy after the absorption of stopped negative pions in heavy nuclei, thick targets of about 2 g/cm² were used. The absolute normalization of the data was done by comparison to the data of Ref. [Har178] for 197Au. Neutron spectroscopy after the absorption of stopped negative pions in the Ni isotopes was performed simultaneously for all four isotopes by using a specially constructed counter S3-system consisting of four separate plastic scintillators S3₁, S3₂, S3₃, S3₄ situated side by side, each holding one of the Ni targets. The insert in Fig.1 shows the geometry of the counter S3-system. The separated Ni isotopes had a thickness of only 100 mg/cm². This lead to a large uncertainty in the absolute normalization of the Ni data. Therefore a further measurement was made by substituting the four Ni isotopes with four identical ¹⁸¹Ta targets in the same geometry, thus providing a relative normalisation of the Ni isotopes to Ta. The simultaneous measurement of the Ni isotopes minimized relative errors in normalization between the different Ni isotopes and improved the statistics.

NEUTRON DETECTORS. Neutrons were detected with four liquid organic scintillators of type NE213 (2" thickness X 5" diameter). The horizontal arrangement of the neutron detectors is shown in Fig.2. The neutron energy was determined by a time-of-flight/ pulse height (TOF/PH) technique, the TOF distance being 2.025 ± 0.025 m from the target to the neutron detector. The time resolution was 1.2 ns FWHM with a neutron detection threshold of 1 MeV. All neutron detectors NE1 - NE4 could discriminate against charged particles, which were tagged by 1 mm thick plastic scintillator counters SH1- SH4 in front of the detectors. A side view of one neutron detection system with shield counter is given in Fig.1. The geometry of a neutron detector is shown in detail in Fig.22 of the appendix. Electronic pulse-shape-discrimination (PSD) was used to identify neutrons and gammas [Rudo74]. The background of scattered neutrons coming from the floor and surrounding walls was measured by placing a cylindrical iron shadow-bar (see Fig.2) into the direct flight path between target and detector [Isaa76], [HarI78], [Eise78]. A discussion of the different types of background is given in section 2.1.3..

The neutron detectors were operated in a wide dynamic range, the upper limit for the neutron energy being given by the pion rest mass (140 MeV) and the lower limit by the intention of fitting the low energy neutrons to an evaporation law. An on-line detection threshold of less than 1 MeV neutron energy was chosen. Two separate dynamic ranges were used to cover the entire range of PH-amplitudes, corresponding to a dynamic range of about 500 due to non-linear light output for ionization by protons as compared to electrons. The low-dynamic range extended from 1 to about 5 MeV; the high-dynamic range, up to 140 MeV neutron energy. This splitting of the dynamic range allowed more refined walk corrections in timing to be made, resulting in better energy resolution as compared to Ref. [HarI78], in the high energy part of the neutron spectrum (see Fig.24 of the appendix). The on-line thresholds were calibrated with radioactive γ -sources (^{137}Cs , ^{22}Na , ^{88}Y ,

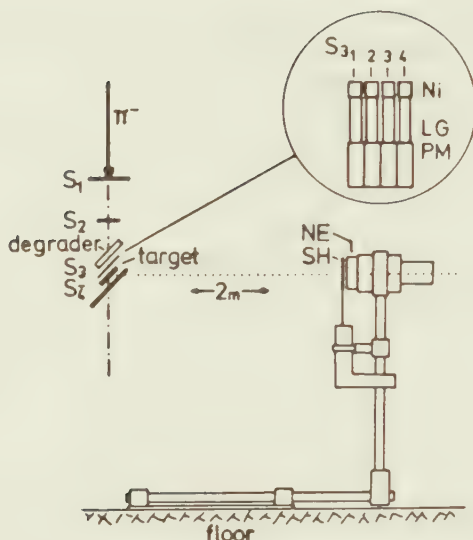


Fig.1 /PION BEAM TELESCOPE. The figure shows the vertical pion beam telescope, consisting of four plastic scintillator counters S1, S2, S3 and S4, with a polyethylene degrader and target, and a side view of a neutron detector NE with shield counter SH. The enlarged insert depicts the special counter S3-system, consisting of four separate plastic scintillators S31, S32, S33 and S34 with light guides LG and photo-multipliers PM. The Ni isotope targets were placed under the scintillators.

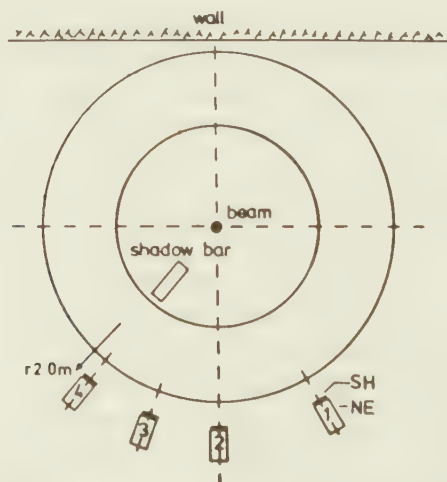


Fig.2 /NEUTRON DETECTOR ARRANGEMENT. The figure shows the neutron detector arrangement around the vertical beam. NE1- NE4 are the neutron detectors and SH1- SH4 1mm thick plastic scintillators (shield counters) used to tag charged particles. The shadow-bar was a cylindrical block of iron used for the measurement of background neutrons scattered from the floor and surrounding walls.

^{60}Co), taking into account the differences in light production between electrons and protons [Dros72] (Fig.19a of the appendix). Threshold calibrations were performed before, during and after each run. The neutron thresholds and photomultiplier gains were determined periodically during the whole experiment. In the off-line analysis the threshold was set at 1 MeV neutron energy. An example of an energy calibration is given in Fig.19b of the appendix. The neutron detection efficiency for a neutron detection threshold of 1 MeV, a thickness of 2" and a diameter of 5", was assumed the same as in Ref. [HarI78] (see Fig.22 of the appendix). The efficiency was calculated with a Monte Carlo computer code for energies between 1 and 50 MeV [HarI78]. Adjusted for one measured value at $E_n = 70$ MeV, the efficiency was extrapolated towards higher energies according to a $1/E_n$ law. This experimental point was determined at the Saclay Linac using a negative pion beam stopped in a liquid deuterium target. The two neutrons emitted back to back at 70 MeV after negative pion absorption in a deuteron were detected in coincidence and the efficiency determined from the ratio of the single and coincidence counting rates of the two detectors. The solid angle of each neutron detector at a distance of 2.025m was $2.435 \cdot 10^{-4}$.

As compared with previous experiments [AndH64], [VenF64], [HatM65] a combination of desirable improvements have been achieved in this work: low neutron threshold (1 MeV vs 1.8 [AndH64], 1.0 [VenF64], 2.5 [HatM65] MeV), good time resolution (1.2 ns FWHM vs 4 [AndH64], 1.6 [VenF64], 2.4 [HatM65] ns FWHM), large time-of-flight distance (2.025 m vs 1.083 [AndH64], 1.5 [VenF64], 2.0 [HatM65] m), and good n- γ -discrimination (vs none [VenF64], [HatM65] or not good enough [AndH64]). The shadow-bar background subtraction [HarI78] and higher statistics are other improvements.

2.1.2. ELECTRONICS FOR NEUTRON SPECTROSCOPY.

A scheme of the electronics used for neutron spectroscopy is given in Fig.3. For the measurements of the heavy nuclei, the pion telescope consisted of the four plastic scintillators S1, S2, S3 and S4, which gave the pion flux $\dot{N}$ and rate of stopped pions N_{stop} used to normalize the neutron data. In the case of the Ni measurements counter S3 was replaced by a system of four counters S_{31} , S_{32} , S_{33} and S_{34} , thus allowing the simultaneous measurement of all four Ni isotopes. The anode signals from the four neutron detectors NE1, NE2, NE3 and NE4 were mixed in a linear fan-in/fan-out and then split into a low and a high dynamic range. The anode signals from the neutron detectors and the stopped pion signal from the pion telescope were used to start and stop, respectively, the time-of-flight (TOF) circuit, consisting of a time-to-amplitude converter (TAC) and an analog-to-digital converter (ADC). If two pions came to rest within the 200 ns measuring time of the TAC, a pile-up signal was generated in the pile-up gate (PG) and used to inhibit the TAC. The time calibration of the TOF circuit was determined with an electronic time calibrator and checked with the 50 MHz cyclotron r.f., which produced periodic structures in the γ -TOF spectra. Pulse height (PH or E) signals were extracted directly from the dynode D-10 of the neutron detectors and fed via a linear gate into a spectroscopic amplifier (MA) coupled to an ADC. Pulse-shape-discrimination was performed with the dynodes D-11 and D-14 of the neutron detectors, allowing the identification of gammas and neutrons (or electrons and protons tagged by the shield counters). The two LABEN 8215 ADC units were interfaced through CAMAC to a PDP 11/20 computer and converted the TOF and PH signals into two 12 bit addresses. These addresses were written on magnetic tape by the on-line computer event by event, each event consisting of two 16 bit words (one TOF and one PH amplitude), 12 bits of which, for each word, were reserved for the ADC addresses ($2^{12} = 4096$ channels per amplitude). The remaining 4 bits of each word (giving

$2^{2 \cdot 4}$ = 256 possible bit patterns) were used to further characterize the event with respect to the neutron detector, which detected the event (NE1, NE2, NE3 or NE4), the kind of particle (neutron, gamma, proton or electron), the dynamic range (low or high) and in the case of the Ni measurements the target detector (^{58}Ni , ^{60}Ni , ^{62}Ni or ^{64}Ni). The correspondence between bits and detector, particle, dynamic range and target is indicated in Fig.3 and described in the figure caption. Various counting rates from the pion telescope, pile-up rates and rates from the neutron detectors, which were used to check and normalize the measurements, were written on magnetic tape record by record, each record consisting of 256 words, the first 24 words of which were reserved for the above mentioned counting rates and one record identifying word, leaving space for 116 events per record.

2.1.3. NEUTRON MEASUREMENTS.

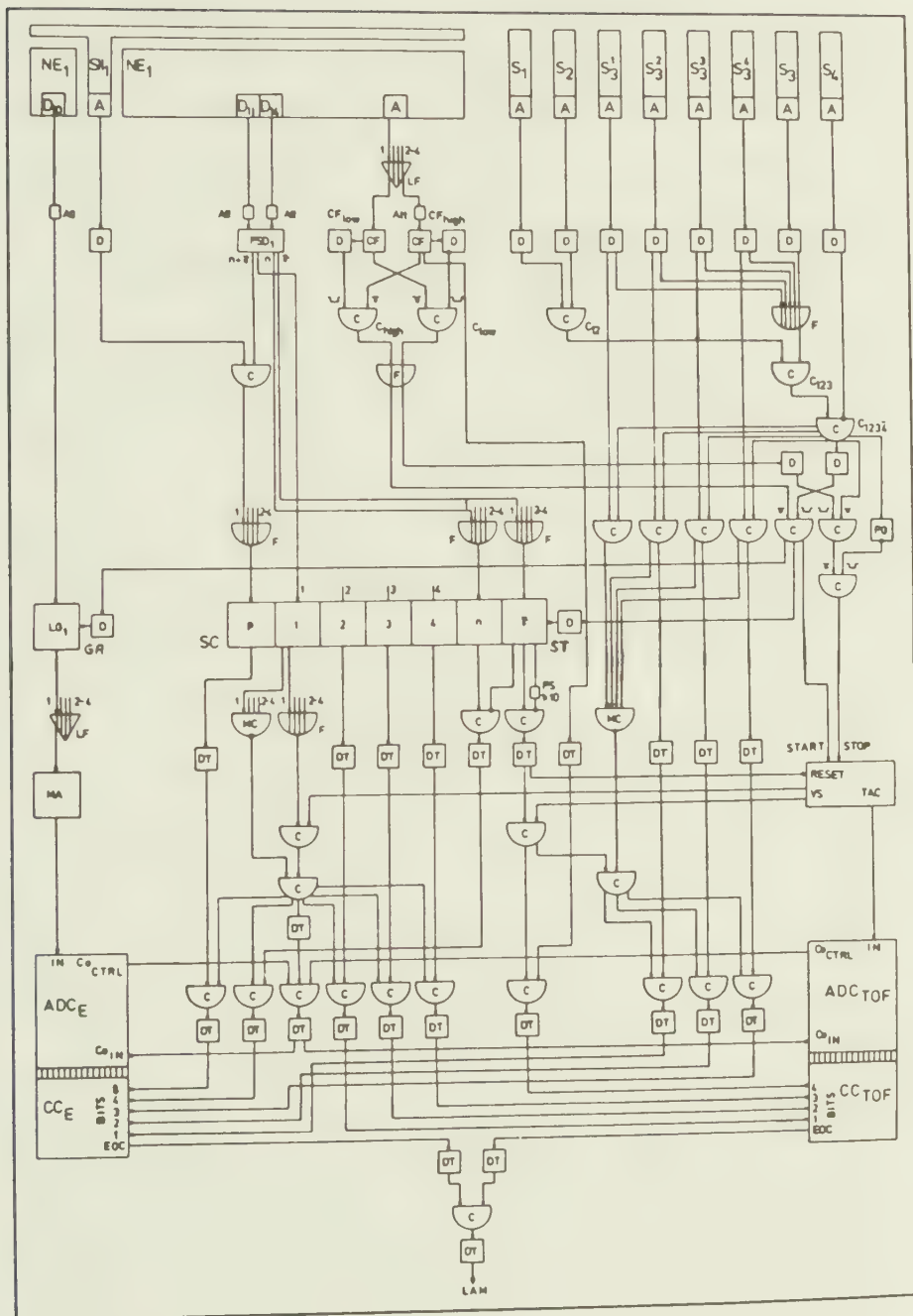
Neutron spectra were measured for a number of heavy nuclei: ^{165}Ho , ^{181}Ta , ^{197}Au , natTl, natPb, ^{209}Bi and ^{238}U , as well as for the four Ni isotopes: ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni . Throughout the measurements of the heavy nuclei ^{197}Au was used as a reference target and was therefore measured in three different runs. This enabled an absolute normalization of the neutron data by comparison with the data of Hartmann et al. [HarI78] for ^{197}Au . The heavy targets were about 2 g/cm² thick, whereas the Ni targets were only about 100 mg/cm². All neutron TOF spectra were measured with the apparatus shown in section 2.1.1., corrected for background as described in section 2.2.1. and then converted to energy spectra as shown in section 2.2.2.. For each target four kinds of measurements were performed: In the target measurement (type m) the neutron TOF spectra were measured with the selected target in position. To be able to correct for different sources of background, the following further measurements were necessary. The empty target measurement (type e) enabled the correction of the measured target

Fig.3 /ELECTRONICS FOR NEUTRON SPECTROSCOPY. Symbol definitions are as follows:

1,2,3,4	NE counter number bit
A	anode (S, SH or NE)
ADC	analog-to-digital converter (for TOF and E)
Att	attenuator
C	coincidence unit
CC	CAMAC coupler (for TOF and E)
CF	constant-fraction timing discriminator
CoCTRL,CoIn	ADC coincidence control, input
D	discriminator
D-10	dynode D-10 (NE)
D-11	dynode D-11 (NE)
D-14	dynode D-14 (NE)
DT	delay trigger
EOC	end-of-conversion signal
F	logic fan (fan-in/fan-out)
GA	gate input for LG
IN	ADC analog input
LAM	computer LAM
LF	linear fan (fan-in/fan-out)
LG	linear gate
low,high	low,high dynamic range
MA	spectroscopic amplifier
MC	majority coincidence unit
NE	neutron detector (liquid organic, type NE213)
p,n,Y	proton, neutron, gamma bit
PS	pre-scaler
PSD	pulse-shape discriminator
RESET	TAC reset
S	plastic scintillator (pion telescope)
SC	strobed coincidence unit
SH	plastic scintillator (shield counter)
START,STOP	TAC start, stop
ST	strobe input for SC
TAC	time-to-amplitude converter
VS	valid stop signal from TAC

The correspondence between bits and neutron detector, particle, dynamic range and Ni target is given by the following table:

bit pattern	TOF ADC	PH ADC	
0	NE1 low	gamma	58Ni
1	NE2 low	gamma	60Ni
2	NE3 low	gamma	62Ni
3	NE4 low	gamma	64Ni
4	NE1 high	neutron	58Ni
5	NE2 high	neutron	60Ni
6	NE3 high	neutron	62Ni
7	NE4 high	neutron	64Ni
8		electron	58Ni
9		electron	60Ni
10		electron	62Ni
11		electron	64Ni
12		proton	58Ni
13		proton	60Ni
14		proton	62Ni
15		proton	64Ni



spectra for background correlated with false π^- -stops in the counter S3 of the pion telescope. This type of background was determined by simply measuring the neutron TOF spectra with the target removed. In the shadow-bar background measurement with target in position (type b), scattered neutrons coming from the floor and surrounding walls were detected with a cylindrical block of iron (=shadow-bar) in the direct flight path between target and neutron detector. This type of background measurement detected both events correlated with true π^- -stops in the target and false π^- -stops in counter S3, already contained in the background measurement of type e. Therefore a further measurement was performed with the shadow-bar in place but the target removed (type eb). In the measurements of the heavy nuclei, the background of neutrons correlated with true π^- -stops (type b) proved to be most important; the contribution of background correlated with false π^- -stops in counter S3 (types e and eb) was at least an order of magnitude smaller. This is of course due to the fact that the targets in this case were much thicker than counter S3. In the case of the Ni measurements, where thin targets were used, the neutron background coming from false π^- -stops in counter S3 (mainly type e) was dominant. Fig.4 illustrates the four different types of neutron TOF measurements for ^{62}Ni . Neutron TOF spectra for the heavy nuclei are all very similar. As an example, a neutron TOF spectrum for ^{197}Au may be found in Fig.7 of Ref. [HarI78]. The corrected neutron TOF spectrum used in the final analysis was produced by subtracting the properly normalized empty target and corrected shadow-bar (shadow-bar minus empty shadow-bar) measurements from the measured target spectrum. The accidental background of neutrons not correlated with any stopped pion signal 1234 from the pion telescope was flat and was of minor importance in the corrected spectrum. It could simply be subtracted from the neutron TOF spectra by taking the random background at negative TOF. This is a demonstration of the usefulness of the shadow-bar measurements. Simply subtracting the empty target from the measured target would not have resulted in a flat accidental

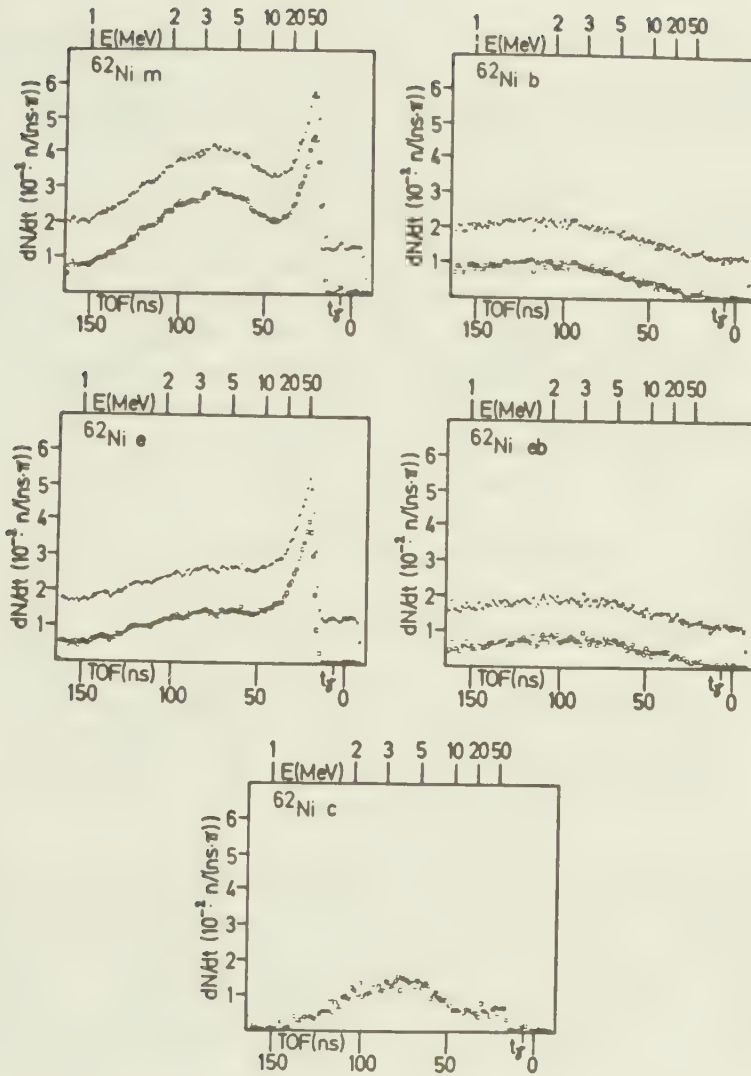


Fig.4 /MEASURED AND BACKGROUND CORRECTED NEUTRON TOF SPECTRA FOR ^{62}Ni . The figure shows the four different types of neutron TOF spectra that were measured for ^{62}Ni and the final corrected neutron TOF spectrum, derived in the way described in the text. m is the measured target, e the empty target, b the shadow bar with target, eb the empty shadow bar measurement and c the corrected TOF spectrum. The spectra m, e, b and eb are shown with (crosses) and without (squares) the flat accidental background. All TOF spectra are absolutely normalized to the number of stopped pions but are not corrected for neutron detection efficiency. t_γ is the TOF of the prompt gammas from the target. Due to imperfect n- γ -discrimination, a small gamma peak can be seen in the measured neutron TOF spectrum.

background. A discussion of the importance of the shadow-bar measurements is given in Ref. [HarI78], where both neutron and gamma spectra are shown. One sees that the main contribution of background events is concentrated at large TOF, indicating that mainly the floor, which was 1.2 m below the target, and the surrounding walls, which were more than 2 m away, are the important sources of background and not material concentrated near the target. The background spectrum of type e with target removed stems from the plastic of counter S3 and therefore strongly resembles a TOF spectrum of neutrons emitted after the absorption of stopped negative pions in ^{12}C (see Fig.4 of Ref. [HarI78]).

2.2. ANALYSIS OF NEUTRON SINGLE SPECTRA.

2.2.1. EVALUATION OF NEUTRON TOF SPECTRA.

For the analysis of the neutron single spectra, all TOF spectra were treated in the same way. First all the measured spectra described in section 2.1.3. were corrected for walk in timing as a function of pulse height (PH) by determining the position of the prompt gamma peak in 16 successive PH intervals for both the low and the high dynamic range, for all four neutron detectors and for all targets separately, although it was seen that in general the walk function was independent of target and only slightly dependent on neutron detector. An example of such a walk function is given in Fig.20 of the appendix for both low and high dynamic range. The importance of a proper correction for walk in timing can be seen very well in the high energy part (small TOF) of the energy spectrum, where a small shift in TOF has a large influence on energy. Comparing the ^{197}Au spectrum from this work with the ^{197}Au spectrum of Hartmann et al. [HarI78] (see Fig.24 of the appendix), where only one dynamic range and 8 PH intervals were used, clearly shows that the present spectrum falls off much more rapidly above about 100 MeV and does not extend up to an kinematically forbidden energy of 150 MeV. In the next step

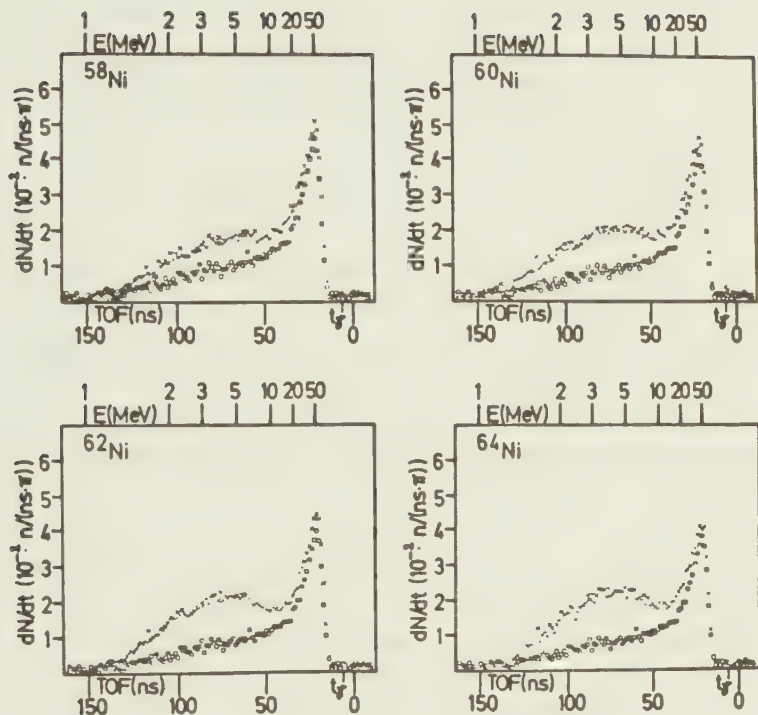


Fig.5 /MEASURED NEUTRON TOF SPECTRA FOR THE Ni ISOTOPEs. The figure shows the shadow bar corrected neutron TOF spectra with (m minus b , crosses) and without target (e minus eb , squares) for the Ni isotopes ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni . The TOF spectra are absolutely normalized to the number of stopped pions but are not corrected for neutron detection efficiency. An isotope effect is clearly seen in the difference of the two spectra (with and without target), which increases with increasing neutron number N of the isotope.

all the measured spectra of types m, e, b and eb belonging to one target were normalized to the rate of incident pions, corrected for beam pile-up (typically 20%) and computer dead time (about 10%). Corrected neutron TOF spectra were then derived as described in section 2.1.3.:

$$c = m - e - (b - eb) - r \quad (2.1)$$

where c is the corrected, m the measured target, e the empty target, b the shadow-bar and eb the empty shadow-bar spectrum. r is the random background (taken at negative TOF), left after the other sources of background have been subtracted. The corrected neutron TOF spectra were then absolutely normalized to the number of stopped pions in the target, taking into account the false π^- -stops in counter S3 of the pion telescope and correcting for beam pile-up and computer dead time. An absolutely normalized and background corrected neutron TOF spectrum is shown in Fig.4 for ^{62}Ni . One clearly sees that the spectrum may be separated into a low energy and a high energy part. The distinction between evaporation and non-evaporation neutrons will be discussed in section 2.2.2.. Fig.5 shows neutron TOF spectra with and without target, but corrected for shadow-bar background, for the four Ni isotopes ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni . The spectra clearly demonstrate that there is a large isotope effect in the evaporation part of the spectra. The non-evaporation part of the spectra is very uncertain because of the extremely large background in this region.

The corrected neutron TOF spectra resulting from the procedure described above were transformed to neutron energy spectra using relativistic kinematics:

$$E = m \cdot c^2 (\gamma - 1), \quad \gamma = 1 / \sqrt{1 - \beta^2}, \quad \beta = v/c, \quad v = d/t \quad (2.2)$$

where E is the kinetic energy of the neutron, $m = 939.5527 \text{ MeV}$ the neutron mass, $d = 2.025 \text{ m}$ the TOF distance and t the TOF. The grouping of TOF channels in the TOF spectra was chosen in such a way as to give a more or less

regular distribution of points in the neutron energy spectrum $dN/dE(E)$. The energy E was given by Eq.(2.2) with t corresponding to the center of the TOF bin and $dE = E_U - E_L$, where E_U and E_L are the energies corresponding to the upper and lower ends of the TOF bin. dN was the absolutely normalized content of the TOF bin corrected for neutron detection efficiency and solid angle (see Fig.21 of the appendix).

2.2.2. INTERPRETATION OF THE NEUTRON ENERGY SPECTRA.

Neutron multiplicity X and mean neutron energy per stopped pion $\langle E \rangle$ and per emitted neutron $\langle E \rangle'$ are given by the following relations:

$$X = \int dN/dE(E) \cdot dE \quad \text{neutron multiplicity (2.3)}$$

$$\langle E \rangle = \int dN/dE(E) \cdot E \cdot dE \quad \text{mean energy per stopped pion (2.4)}$$

$$\langle E \rangle' = \langle E \rangle / X \quad \text{mean energy per neutron (2.5)}$$

In order to obtain the nuclear temperature parameter, the neutron energy spectra had to be separated into a low energy evaporation region and the rest. This was done by fitting the former to the LeCouteur formula [LeCo52], [LeCL59]:

$$dN/dE(E) = Y \cdot E^{5/11} \cdot \exp(-E/\theta) \quad (2.6)$$

where E is the measured neutron energy in MeV, Y a normalization factor and θ the nuclear temperature parameter in MeV, averaged over successive neutron evaporations. θ is related to the temperature T , characteristic of the first neutron emission, by $\theta = 11/12 \cdot T$. For the determination of the two parameters θ and Y the uncompressed TOF spectra were transformed to energy spectra and fitted to Eq.(2.6) in the region between 2.0 and 4.3 MeV. No grouping of TOF channels was used and therefore there were about 100 points in the

fit region, yielding excellent fits to the data and values of θ . As was mentioned already in section 1.2. of the introduction, earlier experiments had also tried to determine θ , but yielded a wild scatter of values for a given target due to scant attention paid to the dependence of the evaluated nuclear temperature parameter θ on the fit region [Halp71]. This dependence was carefully studied and the region from about 2 to 4 MeV was found to be optimal from the points of view of well-known efficiency and negligible contribution from pre-equilibrium neutrons at higher energies. Going below about 1.5 MeV with the lower fit limit brings large uncertainties in the neutron detection efficiency into the fit. Extending the upper limit of the fit above 6 MeV causes a sharp increase in θ due to the increasing importance of the pre-equilibrium neutrons. This fact is clearly illustrated in Fig.6. θ as a function of the upper fit limit, the lower limit being set at 2.0 MeV, is constant only up to about 4.5 MeV and then slowly increases with increasing upper limit. The corresponding reduced χ^2 of the fit has a sharp increase above 4.25 MeV. Setting the upper limit of the fit at 4.25 MeV, one sees that θ as a function of the lower limit is constant. The somewhat higher value of θ for ^{197}Au quoted in Ref. [HarI78], namely $\theta = 1.65$ MeV, as compared with the present value of $\theta = 1.47 \pm 0.07$ (see section 3.1., Tab.1) is largely due to a difference in the fit region for the evaporation neutrons. Hartmann et al. [HarI78] used a region from 2.0 to 5.5 MeV. With the present data, this fit region would give a nuclear temperature parameter $\theta = 1.53 \pm 0.07$. Neutron evaporation multiplicity X_e and mean evaporation energy per stopped pion $\langle E_e \rangle$ and per emitted neutron $\langle E_e \rangle'$ are given by:

$$X_e = Y \cdot \Gamma(16/11) \cdot \theta^{16/11} \quad \text{evaporation multiplicity (2.7)}$$

$$\langle E_e \rangle = Y \cdot \Gamma(27/11) \cdot \theta^{27/11} \quad \text{mean evaporation energy (2.8)}$$

$$\langle E_e \rangle' = 16/11 \cdot \theta \quad \text{mean evaporation energy per neutron (2.9)}$$

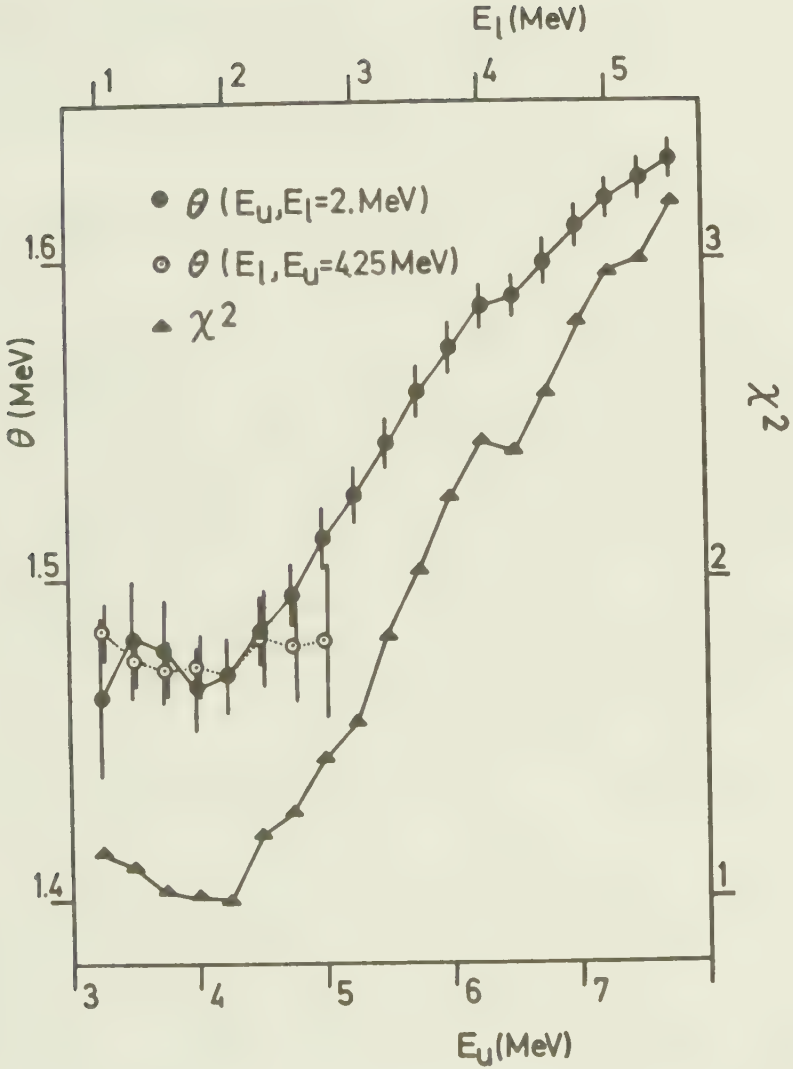


Fig.6 /DEPENDENCE OF THE NUCLEAR TEMPERATURE PARAMETER ON FIT REGION. The figure shows the nuclear temperature parameter θ as a function of the upper E_u and lower E_l limits of the fit region for ^{197}Au . The full circles give θ as a function of E_u , with E_l fixed at 2.0 MeV, along with the corresponding reduced χ^2 of the fit. The open circles show θ as a function of E_l , with E_u fixed at 4.25 MeV. The nuclear temperature parameter is seen to be constant within a fit region of from 1.0 to about 4.5 MeV.

where Γ is the gamma function, $\Gamma(16/11)=0.88563$,
 $\Gamma(27/11)=16/11 \cdot \Gamma(16/11)$.

2.3. CHARGED PARTICLE SPECTROSCOPY.

2.3.1. MECHANICAL SET-UP FOR CHARGED PARTICLE SPECTROSCOPY.

For the measurement of the charged particles p, d, t and α emitted after the absorption of stopped negative pions in the Ni isotopes, the basic set-up described in Ref. [PruE81] was used (see Fig.23 of the appendix). As in the case of the neutron measurements, a pion stop signal was defined with a conventional counter telescope consisting of four plastic scintillators SC1, SC2, SC3 and SC4, two of which (SC3 and SC4) were mounted in the vacuum scattering chamber. The vacuum chamber also contained the target, mounted at 45° to the pion beam, and the charged particle detectors, which were cooled with liquid nitrogen and situated in a plane perpendicular to the beam. For the measurement of the charged particle energy spectra and the identification of the different charged particles p, d, t and α , both a TOF and ΔE -E technique were used. Low energy charged particles were identified with a large silicon surface barrier detector Si of 500 μm thickness and 20 cm^2 area, by simultaneously measuring the energy and TOF over a distance of 0.6 m. High energy charged particles were measured with ΔE -E Si detector telescopes. The ΔE detector was a Si with 500 μm thickness and an area of 2 cm^2 . The E detector consisted of a stack of three lithium drifted silicon crystals Si(Li) with a total thickness of $3.6+3.6+5.0=12.2$ mm and the same area as the ΔE detector. For protons with an energy higher than 51 MeV, corresponding to the total thickness, 12.7 mm, of the ΔE and E detector system, a ΔE_1 - ΔE_2 method of evaluation had to be used, because these high energetic protons lost only a part of their kinetic energy in the E detector. For ^{62}Ni a second measurement was made using a Ge detector with 15 mm thickness and 14 cm^2 area, thus allowing the measurement of

d and t towards higher energies. Further details on the mechanical set-up, the solid state detectors and the electronics in the charged particle measurements are given in Ref. [Hess78], [PruE81], [Senn81].

2.3.2. ANALYSIS OF CHARGED PARTICLE SPECTRA.

The method of analysis for the charged particle spectra was the same as in Ref. [PruE81] and is described in detail in Ref. [Hess78], [Senn81]. The ΔE -E and E-TOF spectra were used to separate the charged particles p, d, t and α . The separated charged particle spectra were then converted into corresponding energy spectra. Using the method of Schlepuetz et al. [SchC79], [ComS76], the energy spectra were then corrected for energy loss and absorption of the charged particles in the target material. An example for such a target absorption correction is given in Fig.7 for ^{62}Ni . Comparing the measured and the corresponding corrected spectra for the absorption of stopped negative pions in ^{62}Ni , one sees that the corrections are quite large for low energies ($E < 15$ MeV).

Because only a small amount (about 1%) of the pions were stopped in the thin Ni targets, no reliable absolute rates of stopped pions in the target could be obtained from the pion telescope. Therefore ^{62}Ni was normalized relatively to ^{59}Co , for which absolute data exist. The absolute normalization of the charged particle data for ^{59}Co is described in detail in Ref. [PruE81]; the method was based on the determination of the absolute rate of stopped pions in a ^{197}Au target by measuring the pionic X-ray spectrum and comparing with known transition intensities.

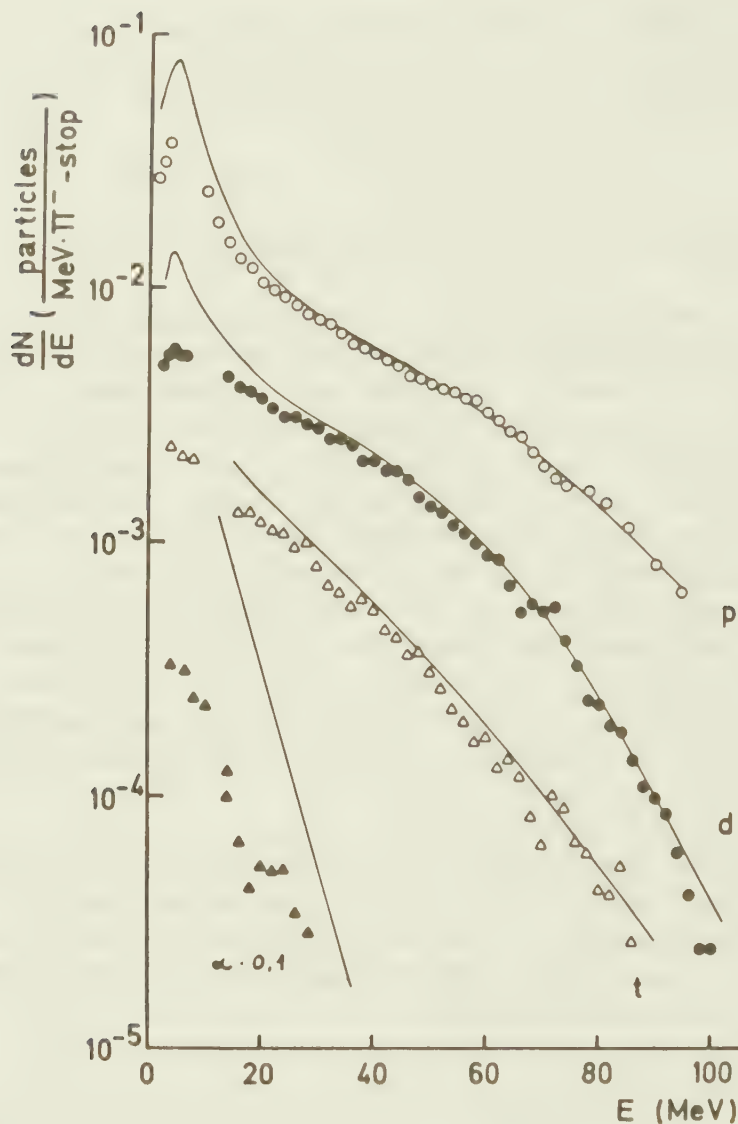


Fig.7 /CHARGED PARTICLE SPECTRA AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN ^{62}Ni WITH CORRECTIONS FOR ENERGY LOSS AND ABSORPTION IN THE TARGET. The figure shows the measured spectra of p (open circles), d (full circles), t (open triangles) and α (full triangles) emitted after the absorption of stopped negative pions in ^{62}Ni . The corresponding energy spectra corrected for energy loss in the target are represented by the solid lines. All spectra are absolutely normalized to the number of stopped pions. Note that the alpha spectra are multiplied by a factor of 0.1.

3. RESULTS AND CONCLUSIONS.

3.1. NEUTRON SPECTROSCOPY AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN THE HEAVY NUCLEI ^{165}Ho , ^{181}Ta , ^{197}Au , natTl , natPb , ^{209}Bi , ^{238}U .

The neutron energy spectra after the absorption of stopped negative pions in the heavy nuclei ^{165}Ho , ^{181}Ta , ^{197}Au , natTl , natPb , ^{209}Bi and ^{238}U are shown in Fig.8 with the corresponding evaporation fits determined with Eq.(2.6). In order to emphasize the low energy parts of the spectra, a log-log representation of the data was chosen. The high energy parts of the spectra are the same for all the measured nuclei. Full numerical tables of the measured neutron spectra are given in Tab.9 of the appendix. An indication of the quality of the evaporation fit to the low energy neutrons is seen in Fig.9., where $dN/dE(E) \cdot E^{-5/11}$ is plotted as a function of E . In this representation Eq.(2.6) is given by straight lines, the slopes of which are inversely proportional to the nuclear temperature parameter θ . Clearly the nuclear temperature parameters θ decrease as a function of target mass number A , except in the special case of ^{238}U , where fission leads to a higher temperature than expected from evaporation alone. A detailed discussion of ^{238}U is given later in this section. Note however, that the fit to a pure evaporation spectrum of the type (2.6) is very good. This is of course due to the fact that the fission spectrum (see Eq.(3.8)) is very similar to the evaporation spectrum (Eq.(2.6)). Tab.1a gives values of the nuclear temperature parameters θ for the heavy nuclei. θ was determined with the fit procedure described in section 2.2.2., the evaporation neutrons being fitted in the energy region between 2.0 and 4.3 MeV. Also given in Tab.1a are the numbers of evaporation and non-evaporation (direct) neutrons as well as the actual number of measured neutrons emitted per stopped pion above thresholds of 1.2, 2.0, 5.0, 10.0, 20.0, 40.0 and 80.0 MeV. The total number of neutrons (evaporation + non-evaporation) emitted per stopped pion was determined

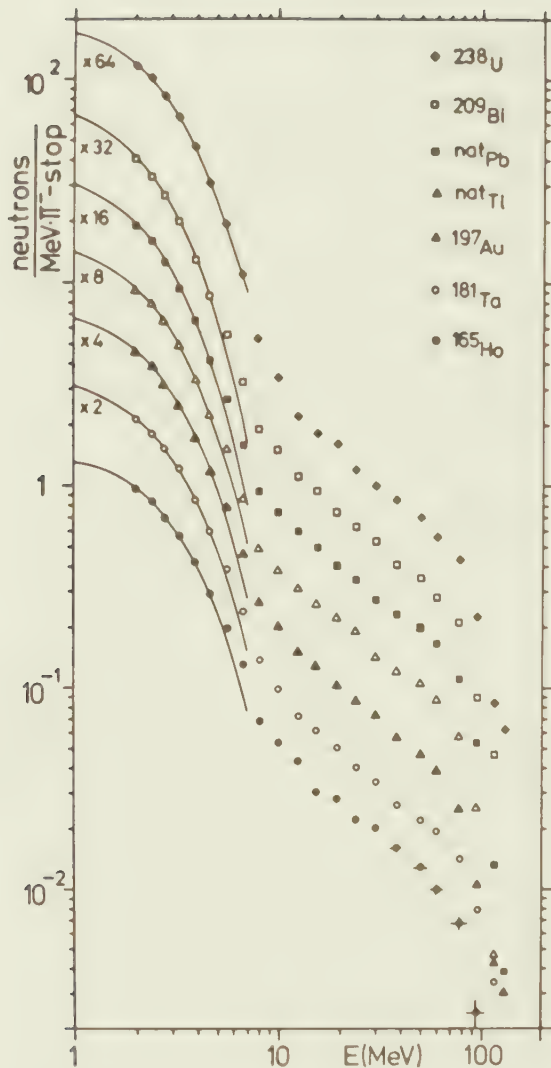


Fig.8 /NEUTRON ENERGY SPECTRA AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN HEAVY NUCLEI. The figure shows the measured spectra of neutrons emitted after the absorption of stopped negative pions in the heavy nuclei ^{165}Ho , ^{181}Ta , ^{197}Au , natTl , natPb , ^{209}Bi and ^{238}U in a log-log representation. The evaporation fits to the low energy neutrons are indicated by the solid lines. The vertical errors indicated in the ^{165}Ho spectrum are statistical only; the overall error in absolute normalization is 15%. The energy resolution, represented by the horizontal error bars for ^{165}Ho , was about 3% at 2 MeV, 4 % at 10 MeV and 10% at 100 MeV. All spectra are normalized to the number of stopped pions. Note that the spectra, starting from ^{181}Ta are successively multiplied by a factor of 2.

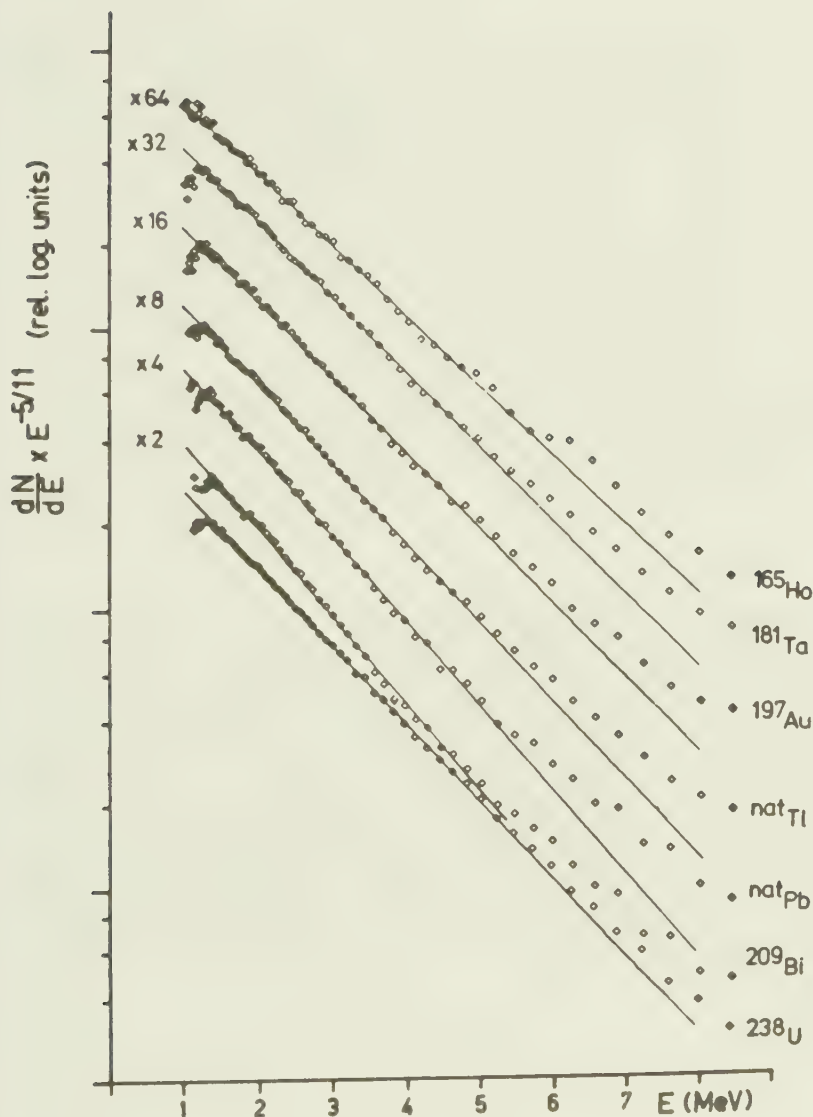


Fig.9 /EVAPORATION FITS FOR HEAVY NUCLEI. The measured spectra of low energy neutrons emitted after the absorption of stopped negative pions in the heavy nuclei are plotted as $\frac{dN}{dE} \cdot E^{-5/11}$ in relative logarithmic units. The solid lines are the evaporation fits to the data in the region between 2.0 and 4.3 MeV. The slopes determine the nuclear temperature parameters θ . For reasons of clarity, not all the data points used in the actual fit are plotted.

	165Ho	181Ta	197Au	natTi	natPb	209Bi	238U	197Au [Har198]	197Au [Prü879]
θ [MeV]	1.64(8)	1.53(8)	1.47(7)	1.42(7)	1.35(7)	1.30(7)	1.51(8)	1.65	
X_m [n/π] $E > 1.2$ MeV	4.3 (7)	4.4 (8)	4.5 (7)	4.6 (7)	4.5 (7)	4.6 (7)	6.5 (11)		
$E > 2.0$ MeV	3.5 (5)	3.5 (6)	3.5 (5)	3.6 (6)	3.5 (5)	3.4 (5)	4.8 (8)	3.7	
$E > 5.0$ MeV	1.8 (3)	1.8 (3)	1.8 (3)	1.8 (3)	1.7 (3)	1.6 (3)	1.9 (3)		
$E > 10.0$ MeV	1.3 (2)	1.2 (2)	1.2 (2)	1.3 (2)	1.3 (2)	1.1 (2)	1.2 (2)		
$E > 20.0$ MeV	0.95(15)	0.91(16)	0.89(14)	0.96(15)	0.93(14)	0.84(13)	0.86(14)	0.9	
$E > 40.0$ MeV	0.5 (1)	0.6 (1)	0.5 (1)	0.6 (1)	0.6 (1)	0.5 (1)	0.5 (1)		
$E > 80.0$ MeV	0.10(2)	0.16(2)	0.12(2)	0.12(2)	0.14(2)	0.12(2)	0.15(2)		
X_e [n/π] $E > 0.0$ MeV	4.4 (7)	4.8 (9)	5.1 (8)	5.2 (9)	5.4 (9)	5.7 (9)	8.3 (14)	4.99	
$E < 1.2$ MeV	1.5 (2)	1.8 (3)	2.0 (3)	2.1 (4)	2.3 (4)	2.5 (4)	3.1 (5)		
X_t [n/π] $E > 0.0$ MeV	5.8 (7)	6.2 (9)	6.5 (8)	6.7 (8)	6.8 (8)	7.1 (8)	9.6 (12)	6.31(36)	
X_d [n/π] $E > 4.3$ MeV	1.4 (3)	1.4 (3)	1.4 (3)	1.5 (3)	1.4 (3)	1.4 (3)	1.3 (3)	1.32(10)	
$\langle n \rangle$ [n/π]			6.7 (8)					6.5 (4)	6.6 (4)

Tab.1a/RESULTS FROM NEUTRON SPECTROSCOPY IN HEAVY NUCLEI: NUCLEAR TEMPERATURE PARAMETERS AND NEUTRON MULTIPLICITIES. Nuclear temperature parameters θ and neutron multiplicities X are given for the heavy nuclei 165Ho, 181Ta, 197Au, natTi, natPb, 209Bi and 238U. θ was determined from an evaporation fit to the data in the energy region from 2.0 to 4.3 MeV. The nuclear temperature of the residual nucleus after the emission of the first evaporation neutron is $T = \theta \cdot 12/11$. Symbol definitions are as follows: X_m : measured neutron multiplicities for different thresholds of 1.2, 2.0, 5.0, 10.0, 20.0, 40.0 and 80.0 MeV; X_t , X_e , X_d : total, evaporation and non-evaporation (direct) multiplicities, $X_t = X_m(E > 1.2 \text{ MeV}) + X_e(E < 1.2 \text{ MeV})$ and $X_d = X_t - X_e$, where X_e is the contribution of evaporation neutrons emitted with an energy less than 1.2 MeV. $\langle n \rangle$ is the mean number of emitted neutrons per stopped pion, including neutrons bound in the charged particles d, t and α [Prü881].

	¹⁶⁵ Ho	¹⁸¹ Ta	¹⁹⁷ Au	natTl	natPb	²⁰⁹ Bi	²³⁸ U	¹⁹⁷ Au [Har178]
<Ee> [MeV/ π]	10.6 (16)	10.7 (16)	10.7 (16)	10.9 (16)	10.8 (16)	10.9 (16)	18.0 (30)	12.0
<Et> [MeV/ π]	63. (9)	65. (10)	62. (9)	65. (10)	65. (10)	60. (9)	69. (11)	71.2
<Ed> [MeV/ π]	52. (8)	54. (8)	51. (8)	54. (8)	54. (8)	49. (7)	51. (8)	59.2
<Ee>' [MeV/n]	2.39(12)	2.23(11)	2.14(11)	2.07(10)	1.96(10)	1.89(9)	2.20(11)	2.40
<Et>' [MeV/n]	10.9 (11)	10.5 (11)	9.5 (10)	9.7 (10)	9.6 (10)	8.5 (9)	7.2 (7)	11.3
<Ed>' [MeV/n]	37. (4)	39. (4)	36. (4)	36. (4)	39. (4)	35. (4)	39. (4)	44.9

Tab.1b/RESULTS FROM NEUTRON SPECTROSCOPY IN HEAVY NUCLEI: MEAN ENERGIES. Mean energies are given for the heavy nuclei ¹⁶⁵Ho, ¹⁸¹Ta, ¹⁹⁷Au, natTl, natPb, ²⁰⁹Bi and ²³⁸U. Symbol definitions are: <Et>, <Ee>, <Ed>, <Et>', <Ee>', <Ed>': mean energies of total, evaporation and direct neutrons per stopped pion and per emitted neutron (primed).

from the measured number of neutrons emitted above a threshold of 1.2 MeV; the contribution of neutrons emitted with an energy less than 1.2 MeV was estimated by Eq.(2.6). This contribution strongly depends on A, it increases from 1.5 ± 0.2 neutrons per stopped pion for ¹⁶⁵Ho to 2.5 ± 0.4 for ²⁰⁹Bi and 3.1 ± 0.5 for ²³⁸U. The number of neutrons emitted per stopped pion with an energy higher than 1.2 MeV increases only slightly as a function of A, from 4.3 ± 0.7 for ¹⁶⁵Ho to 4.6 ± 0.7 for ²⁰⁹Bi. For ²³⁸U the corresponding number is somewhat higher due to fission, namely 6.5 ± 1.1 neutrons per stopped pion. Increasing the threshold to 2.0 MeV, one sees that the number of emitted neutrons is roughly the same for all heavy nuclei, about 3.5 ± 0.6 , except in the case of ²³⁸U, where 4.8 ± 0.7 neutrons are emitted per stopped pion. The number of non-evaporation neutrons emitted per stopped pion is 1.4 ± 0.3 for all nuclei; the number of evaporation neutrons increases with increasing mass number A from 4.4 ± 0.3 for ¹⁶⁵Ho to

	165Ho	181Ta	197Au	natTi	natPb	209Bi	238U
A	165	181	197	204.4	207.3	209	238
A' = A - 2.7	162	178	194	202	205	206	235
θ [MeV]	1.64(8)	1.53(8)	1.47(7)	1.42(7)	1.35(7)	1.30(7)	
τ [MeV] = 12/11 θ	1.79(9)	1.67(9)	1.60(8)	1.55(8)	1.47(8)	1.42(8)	
<Ui>-Bi = 47. MeV:							
a [MeV ⁻¹]	14.7 (15)	16.9 (17)	18.4 (18)	19.6 (20)	21.8 (22)	23.3 (23)	
a' [MeV]	11.0 (11)	10.5 (11)	10.5 (11)	10.3 (10)	9.4 (9)	8.8 (9)	
θ_c [MeV] (a' = 8. MeV)	1.40	1.33	1.28	1.25	1.24	1.24	1.16
<Ui>-Bi = 57. MeV:							
a [MeV ⁻¹]	17.8 (18)	20.4 (20)	22.3 (22)	23.7 (24)	26.4 (26)	28.3 (28)	
a' [MeV]	9.1 (9)	8.7 (9)	8.7 (9)	8.5 (9)	7.8 (8)	7.2 (7)	
θ_c [MeV] (a' = 8. MeV)	1.54	1.47	1.40	1.38	1.37	1.36	1.29
<Ui>-Bi = 67. MeV:							
a [MeV ⁻¹]	20.9 (21)	24.0 (24)	26.2 (26)	27.9 (28)	31.0 (31)	33.2 (33)	
a' [MeV]	7.8 (8)	7.4 (7)	7.4 (7)	7.2 (7)	6.6 (7)	6.2 (6)	
θ_c [MeV] (a' = 8. MeV)	1.67	1.59	1.52	1.49	1.48	1.48	1.38

Tab.2 /COMPARISON OF NUCLEAR TEMPERATURE PARAMETERS WITH STATISTICAL THEORY. The experimental nuclear temperature parameters θ are compared with predictions θ_c from statistical theory [Weis37] using the relation $\theta_c = 11/12 \cdot \sqrt{((\langle U_i \rangle - B_i)/a)}$, where $a = A'/8$ is the level density parameter, A' the mass number and $\langle U_i \rangle - B_i$ the mean excitation energy of the residual nucleus after emission of the first evaporation neutron. The nuclear temperature τ connected with the emission of the first neutron is $\tau = 12/11 \cdot \theta$. $\langle U_i \rangle - B_i$ was determined from the mean energy per stopped pion of the fast neutrons and protons to be $\langle U_i \rangle - B_i = 57. \pm 10$. MeV. a and a' are the predictions for the level density parameters a and the factors $a' = A'/a$ taking the measured nuclear temperatures as inputs and using the same relation as mentioned above.

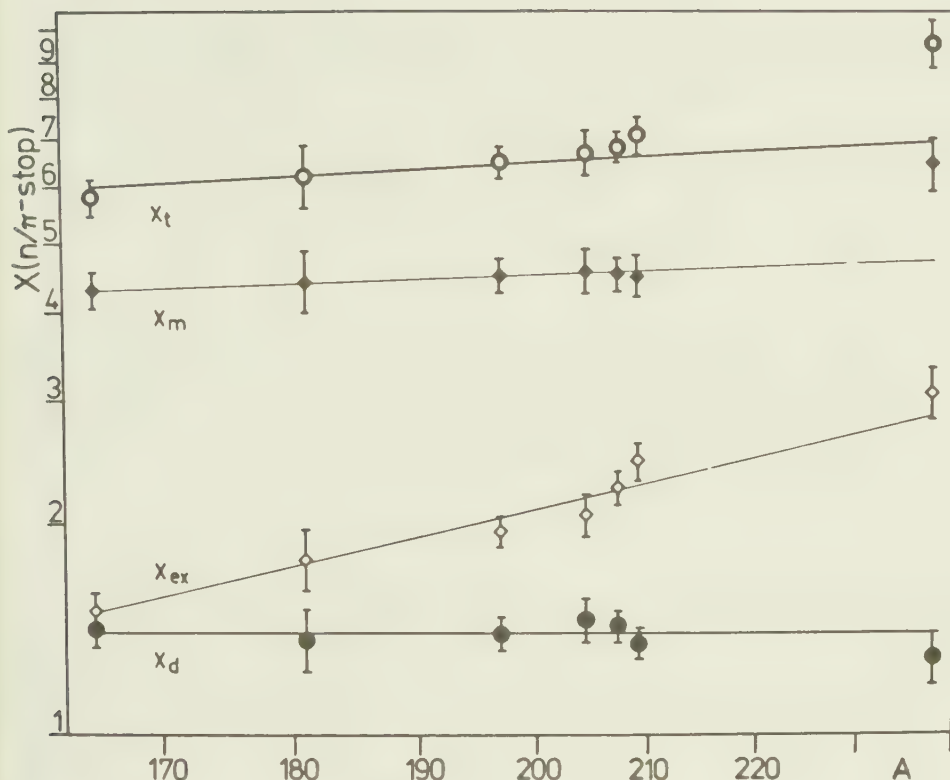


Fig.10/A-DEPENDENCE OF NEUTRON MULTIPLICITIES FOR HEAVY NUCLEI. The neutron multiplicities of direct X_d (= non-evaporation, full circles) and total X_t (= evaporation + non-evaporation, open circles) neutrons, as well as neutrons X_m , X_{ex} emitted per stopped pion with an energy higher (full triangles) and lower (open triangles) than 1.2 MeV are plotted as a function of mass number A in a log-log representation. X_m is the measured number of neutrons emitted per stopped pion; X_{ex} was estimated by Eq.(2.6) and $X_t = X_m + X_{ex}$. The evaporation multiplicity is given by $X_e = X_t - X_d$. The solid lines are power fits to the data from ^{165}Ho to ^{209}Bi : $X_t = 0.78 \cdot A^{0.4}$, $X_m = 1.43 \cdot A^{0.22}$, $X_e = 1.54 \cdot 10^{-4} \cdot A^{1.8}$ and $X_d = 1.4$ neutrons per stopped pion. The errors shown are relative errors between the different targets, an overall error in absolute normalization of 15% must be included for the total error.

5.7 ± 0.9 for ^{209}Bi and 8.3 ± 1.4 for ^{238}U . The above mentioned trends are illustrated in Fig.10. Power functions were fitted to the data and are also shown. Contained in Tab.1b are the mean energies carried away by neutrons emitted after the absorption of stopped negative pions in the heavy nuclei both per stopped pion and per emitted neutron for total, evaporation and direct neutrons.

Using the charged particle data from Pruys et al. [PruE81] one can set up the following energy balance for stopped negative pion absorption in ^{197}Au :

$$E_{\pi} - E_r - B_{\pi} + M(A, Z) - M(A, Z-1) = \langle E_n \rangle + \langle E_c \rangle + \langle E_g \rangle + \langle E_b \rangle, \quad (3.1)$$

with $E_{\pi} = 139.6$ MeV the pion rest mass, E_r the recoil energy of the nucleus ($E_r < E_{\pi}$), $B_{\pi} = 1.5$ MeV the binding energy of the pion in the 4f state and M the nuclear mass, $M(A, Z) - M(A, Z-1) = -1.2$ MeV, $\langle E_n \rangle$, $\langle E_c \rangle$ and $\langle E_g \rangle$ the mean kinetic energies of the emitted neutrons, charged particles and gammas respectively, and $\langle E_b \rangle$ the mean binding energy of the emitted particles per stopped pion. With $\langle E_n \rangle = 62. \pm 9.$ MeV [this work], $\langle E_c \rangle = 12. \pm 2.$ MeV [PruE81], $\langle E_g \rangle \approx 7. \pm 1.$ MeV $B = 7.5$ MeV and $\langle E_b \rangle = 7.5 \cdot (6.9 \pm 0.8) \text{ MeV} = 52. \pm 6.$ MeV [this work], [PruE79], [PruE81] Eq.(3.1) is well fulfilled:

$$E_{\pi} - E_r - B_{\pi} + M(A, Z) - M(A, Z-1) = 137. \text{ MeV} \quad (3.2)$$

$$\langle E_n \rangle + \langle E_c \rangle + \langle E_g \rangle + \langle E_b \rangle = 133. \pm 11. \text{ MeV} \quad (3.3)$$

The mean excitation energy $\langle U_i \rangle$ of the compound nucleus after the direct stage of the absorption process can be estimated from the mean kinetic energies per stopped pion of the fast particles. For ^{197}Au $X_d = 1.4 \pm 0.3$ direct neutrons with an mean energy of $\langle E_n \rangle = 51. \pm 8.$ MeV [this work] and about $X_c = 0.25 \pm 0.05$ fast charged particles with a total energy of $\langle E_c \rangle = 9. \pm 2.$ MeV [PruE81] are emitted per stopped pion. The mean binding energy of these fast particles is $\langle E_b \rangle = 7.5 \cdot (X_d + X_c) = 12. \pm 2.$ MeV and the mean excitation energy

	165Ho		181Ta		197Au		natTi		natPb		209Bi		238U	
	measured	calc	measured	calc	measured	calc	measured	calc	measured	calc	measured	calc	measured	calc
θ [MeV]	1.64(8)	1.59	1.53(8)	1.55	1.47(7)	1.47	1.42(7)	1.46	1.35(7)	1.46	1.30(7)	1.43	1.51(8)	1.65
X_m [n/π] $E > 2$ MeV	3.5 (5)	3.8	3.5 (6)	3.9	3.5 (5)	3.8	3.6 (6)	3.9	3.5 (5)	3.8	3.4 (5)	3.8	4.8 (8)	5.1
$E > 20$ MeV	0.95(15)	0.82	0.91(16)	0.82	0.89(14)	0.80	0.96(15)	0.81	0.93(14)	0.81	0.84(13)	0.84	0.86(14)	0.81
X_e [n/π] $E > 0$ MeV	4.4 (7)	5.5	4.8 (9)	5.8	5.1 (8)	5.9	5.2 (9)	6.0	5.4 (9)	5.9	5.7 (9)	5.9	8.3 (14)	8.9
X_t [n/π] $E > 0$ MeV	5.8 (7)	6.9	6.2 (9)	7.2	6.5 (8)	7.3	6.7 (8)	7.5	6.8 (8)	7.4	7.1 (8)	7.4	9.6 (12)	10.4
X_d [n/π] $E > 4.3$ MeV	1.4 (3)	1.4	1.4 (3)	1.4	1.4 (3)	1.4	1.5 (3)	1.5	1.4 (3)	1.5	1.4 (3)	1.5	1.3 (3)	1.5

Tab.3 /COMPARISON OF NUCLEAR TEMPERATURE PARAMETERS AND NEUTRON MULTIPLICITIES WITH CALCULATIONS. Symbol definitions are as in Tab.1a. Measured X_m above 2 and 20 MeV, total X_t , evaporation X_e and direct X_d neutron multiplicities are compared with the calculations of Kozlowski and Zglinski [KozZ80].

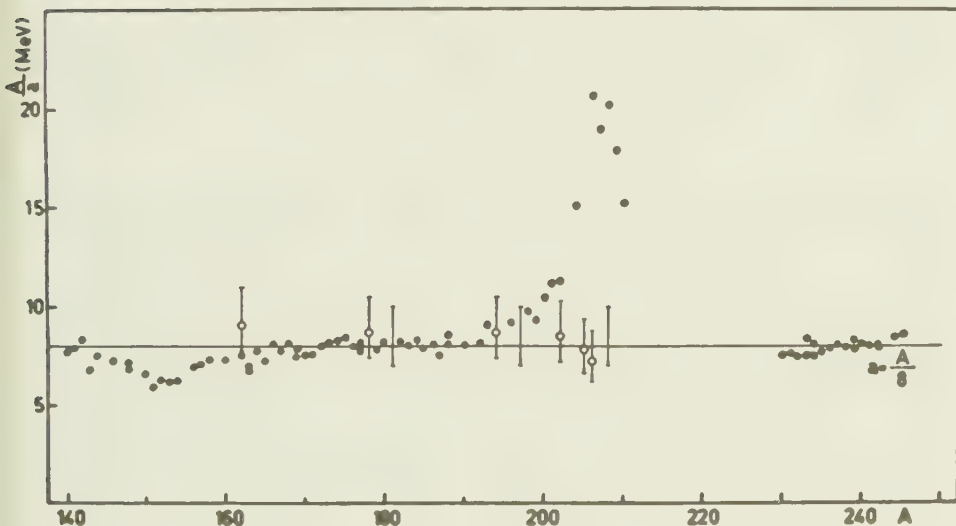


Fig.11/A-DEPENDENCE OF LEVEL DENSITY PARAMETER FOR HEAVY NUCLEI. A/a , with a the level density parameter, is plotted as a function of mass number A . The stopped negative pion data from [this work] (open circles) are compared with results from intermediate energy (α, α') reactions on ^{181}Ta , ^{197}Au and natPb [CheH68] (indicated by the error bars) and with low energy neutron resonance data [Baba70] (points). The strong shell effects in the low energy data are not present in the intermediate energy data, where a value $a = A/8$ [MeV^{-1}] for all nuclei is indicated (solid line).

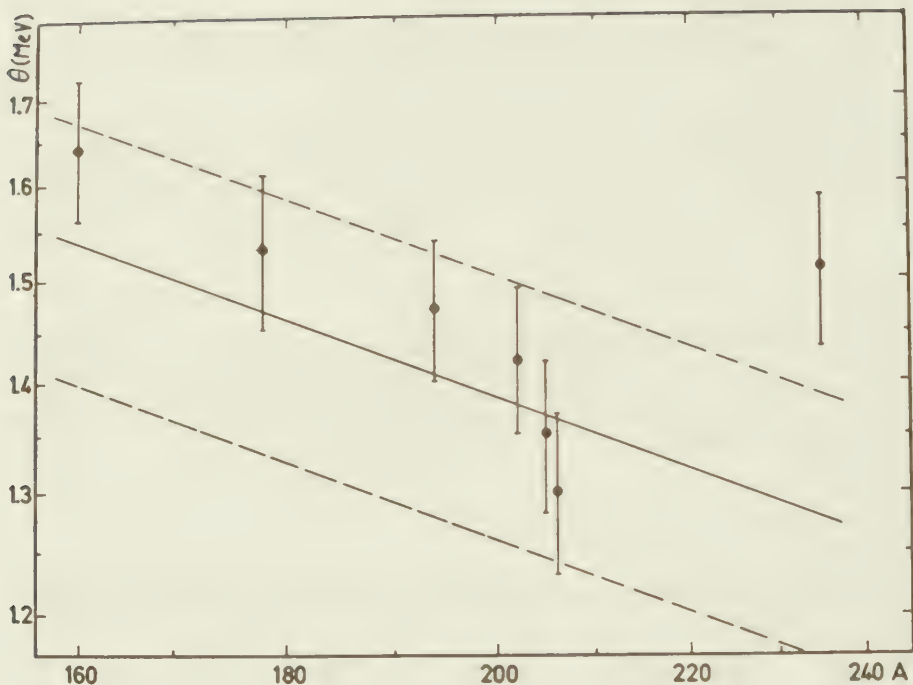


Fig.12/A-DEPENDENCE OF NUCLEAR TEMPERATURE PARAMETERS FOR HEAVY NUCLEI. The nuclear temperature parameters θ for the heavy nuclei ^{165}Ho , ^{181}Ta , ^{197}Au , natTl , natPb , ^{209}Bi and ^{238}U are plotted as a function of A , where A is the mass number of the residual nucleus after the emission of the first evaporation neutron. The nuclear temperature parameters θ were extracted from a fit to the experimental data of the form $dN/dE \sim E^{5/11} \cdot \exp(-E/\theta)$. Note that both the A and the θ axis are on a logarithmic scale. The errors given for θ are absolute errors. The full (dashed) lines give the predictions for θ using the relation $\theta = 11/12 \cdot \sqrt{(\langle U_i \rangle - B_i)/a}$, where $a = A/8 \text{ [MeV}^{-1}]$ is the level density parameter and $\langle U_i \rangle - B_i = 57$. MeV (full line) or $\langle U_i \rangle - B_i = 47$. and 67 . MeV (dashed lines) the mean excitation energy of the residual nucleus extracted from the measured high energy neutron and charged particle spectra as described in the text.

$$\begin{aligned} \langle U_i \rangle &= E_{\pi} - E_r - B_{\pi} + M(A, Z) - M(A, Z-1) - \langle E_n \rangle - \langle E_c \rangle - \langle E_b \rangle = \\ &= 65. \pm 10. \text{ MeV}. \end{aligned} \quad (3.4)$$

The mean excitation energy relevant for the nuclear temperature is

$$\langle U \rangle = \langle U_i \rangle - B_i = 57. \pm 10. \text{ MeV} \quad (3.5)$$

In Tab.2 the measured nuclear temperature parameters θ and the derived level density parameters a are given for mean excitation energies $\langle U \rangle = 57. \pm 10. \text{ MeV}$ using Eq.(1.21). In Fig.11 A/a , where A is the mass number of the residual nucleus after the emission of the first neutron, is plotted as a function of A . The stopped negative pion absorption data are compared with results from intermediate energy (α , α') reactions on ^{181}Ta , ^{197}Au and $^{\text{nat}}\text{Pb}$ [CheH68] and with neutron resonance data [Baba70]. The strong shell effects in the low energy data are not present in the intermediate energy data. This disappearance of shell effects at high excitation energies was also observed in an analysis of 190 MeV proton induced reactions [LeCL59]. The empirical relation

$$a = A/8 \text{ [MeV}^{-1}] \quad (3.6)$$

is in good agreement with the intermediate energy data.

The present simple analysis is based on an experimentally extracted mean excitation energy. An other analysis using a calculated mean excitation energy gives essentially the same results [MukH79], [IsaZ80].

In the model of Kozlowski and Zgliniski [KozZ80] the neutron spectra and the extracted temperatures θ were calculated using energy dependent level density parameters a and energy shifts Δ , with the asymptotic values $a_{\infty} = A/8$ and Δ_{∞} . For the ratio R of absorbing np to pp pairs, the statistical ratio $R' = 2N/(Z-1)$ was taken. The calculated

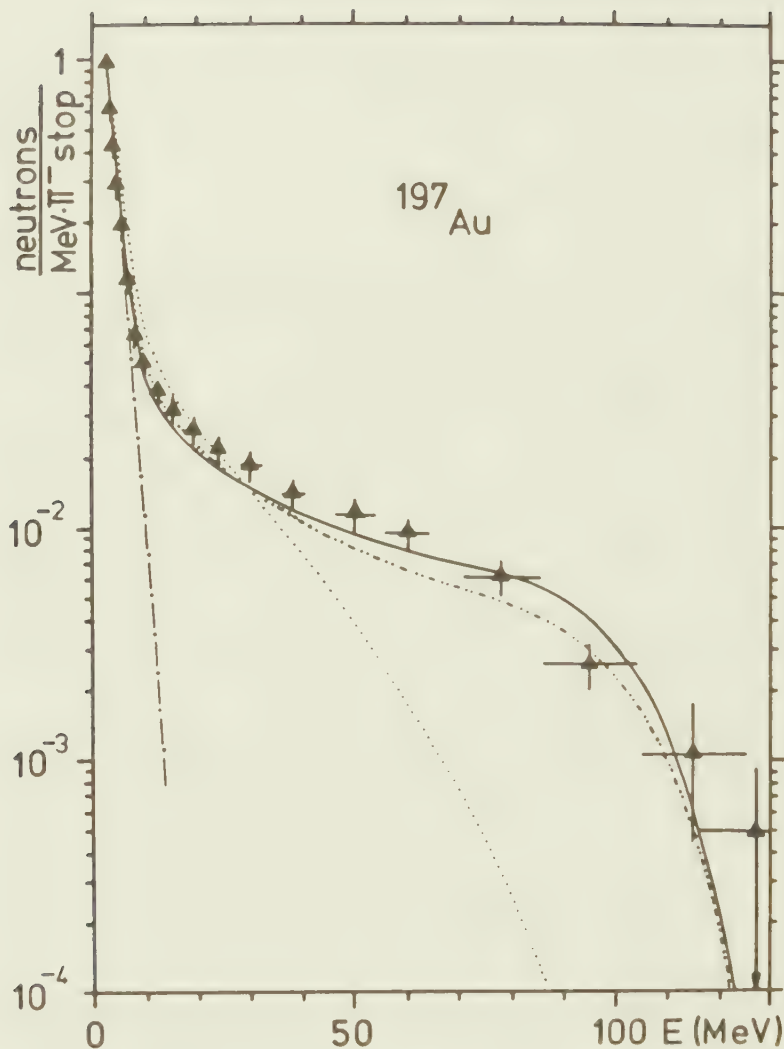


Fig.13/COMPARISON OF MEASURED NEUTRON SPECTRA AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN ^{197}Au WITH CALCULATIONS [KozZ80]. The full triangles represent the measured data. The dot-dashed line shows the evaporation part of the measured spectrum. The solid line gives the results of the calculations [KozZ80] described in the text, assuming pion absorption on a peripheral nucleon pair. The results of the same calculations assuming a 30% and 100% contribution of pion absorption on a four nucleon cluster are indicated by the dotted and the dotted-dashed lines respectively. Clearly a contribution of about 30% may be tolerated, whereas 100% is ruled out.

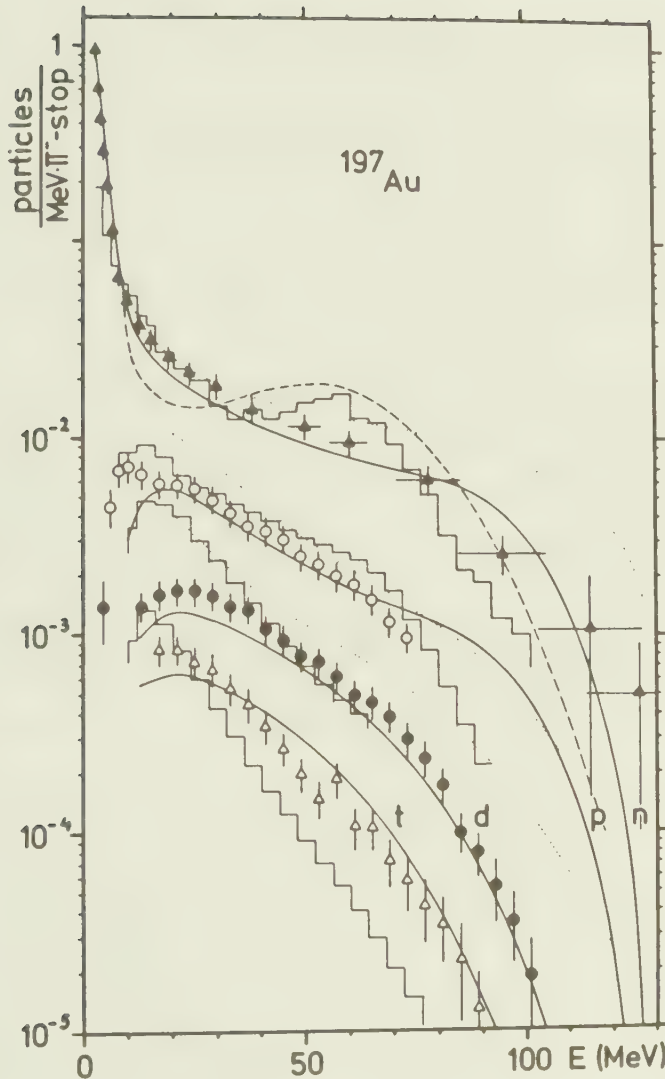


Fig.14/COMPARISON OF MEASURED NEUTRON AND CHARGED PARTICLE SPECTRA AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN ^{197}Au WITH CALCULATIONS. The measured spectra of neutrons [this work] (full triangles), protons (open circles), deuterons (full circles) and tritons (open triangles) [PruE81] emitted after stopped negative pion absorption in ^{197}Au are compared with different calculations assuming pion absorption on a peripheral nucleon pair. The calculations of Kozłowski and Zgliniski [KozZ80], assuming a ratio $R=2.0$ are represented by the solid lines. The dashed line is from Gadioli and Gadioli-Erba [GadG76] with $R=4.0$. The calculations of Iljinov et al. [Ilj 76] are represented by the histograms and the calculations of Chiang and Huefner [ChiH81] by the dotted lines.

nuclear temperature parameters were extracted from the calculated neutron spectra in the same way as the corresponding experimental numbers. Calculated and experimental total neutron multiplicities are compared in Tab.3. The calculated number of neutrons per π^- -stop with energies greater than 20 MeV is about 0.82 per stopped pion for all nuclei, in agreement with the experimental value 0.90 ± 0.15 . The calculated and experimental numbers of neutrons with energies above 2 MeV are 3.8 and 3.5 ± 0.5 per stopped pion in all cases except ^{238}U (for ^{238}U , these are 5.1 and 4.8 ± 0.7 per stopped pion). Fig.13 shows the experimental and calculated neutron spectrum for ^{197}Au . Also shown are the results of the calculations, assuming 100 and 30% pion absorption on a four nucleon cluster. Clearly the data indicate that at most a 30% contribution of absorption on four nucleons may be tolerated. In Fig.14 measured and calculated neutron and charged particle spectra are compared for ^{197}Au . The calculations are from Kozlowski and Zgliniski [KozZ80], Gadioli and Gadioli-Erba [GadG76], Iljinov et al. [IljN76] and Chiang and Huefner [ChiH81].

Comparing with earlier results (see Fig.25a/b/c and Tab.8a of the appendix) from neutron spectroscopy after the absorption of stopped negative pions in heavy nuclei one may conclude that the measured nuclear temperature parameters from this work are in agreement with the results of Isaak [Isaa76] and Hartmann et al. [HarI78], there is rough agreement with Anderson et al. [AndH64] and no agreement with Venuti et al. [VenF64] and Hattersley et al. [HatM65], which give too high numbers. The same agreement or disagreement is naturally also found for the neutron evaporation multiplicities and mean energies. This discrepancy comes largely from the fact that in the Ref. [VenF64] and Ref. [HatM65] the fit region for the evaporation neutrons extended on up to about 15. MeV, whereas the other references used a region between about 2 and 5 MeV. The present total neutron multiplicities agree with the corresponding values of Hartmann et al. [HarI78], roughly agree with the numbers of Anderson et al. [AndH64]

and Hattersley et al. [HatM65] and do not agree with the number of Venuti et al. [VenF64] for ^{nat}Pb , which is too high. γ -ray activation measurements [PruE79] are in agreement with the present total neutron multiplicities. The mean energies carried away by the direct neutrons are in rough agreement with all other references except [VenF64], which gives very small numbers, probably due to the fact that the neutron spectra were measured only up to 50 MeV.

THE SPECIAL CASE OF ^{238}U . For pion absorption in ^{238}U , the fission probability is large [BatG76], [MosF77], [MukH79] and the experimental spectrum yields a "temperature" characteristic of the superposition of evaporation neutrons before any fission (pre-fission neutrons) and those from the fission product fragments (post-fission neutrons). In the simplest interpretation, the low energy neutron spectrum is fitted by the formula

$$dN/dE(E) = \alpha_1 dN_1/dE(E)/I_1 + \alpha_2 dN_2/dE(E)/I_2, \quad (3.7)$$

$$dN_1/dE(E) = \exp(-E/\theta_f) \sinh(2\sqrt{E \cdot E_f}/\theta_f), \quad (3.8)$$

$$dN_2/dE(E) = \exp(-E/\theta) E^{5/11}, \quad (3.9)$$

$$I_i = \int dN_i/dE(E) dE, \quad (i=1,2), \quad (3.10)$$

$$I_1 = \sqrt{\pi \cdot E \cdot \theta_f} \cdot \exp(-E_f/\theta_f) \quad (3.11)$$

$$I_2 = (16/11) \cdot \theta^{16/11}, \quad (3.12)$$

where $dN_1/dE(E)$ [Watt52], [Terr59], [Terr62] represents the post-fission neutrons, $dN_2/dE(E)$ [LeCo52] the pre-fission neutron spectrum, with a temperature $\theta = 1.29$ MeV taken from Tab.2, calculated using Eq.(1.21) for an excitation energy of 57. MeV and $a = A/8$. Assuming symmetric fission, E_f , the most probable kinetic energy released in fission per nucleon is given by the empirical relation [Viol66]

$$E_f = A^{-1} (0.1071 \cdot Z^2 \cdot A^{-1/3} + 22.2) = 0.7 \text{ MeV}. \quad (3.13)$$

One further constraint is obtained by the use of the energy balance equation for the fission fragment [KapR63], [MadN79]

$$a_f (9/8 \theta_f)^2 = 0.5 \alpha_1 \bar{E} + \bar{E}_\gamma, \quad (3.14)$$

where a_f is the fragment level-density parameter $a_f = A/8 = 15 \text{ MeV}^{-1}$ for the fragment mass number $A = 119$, $\bar{E} = E_B + 3/2 \cdot \theta_f$, the average energy per neutron emission from the fragment, E_B the mean neutron binding energy in the fragment ($\sim 5.4 \text{ MeV}$) and $\bar{E}_\gamma$ the residual energy in the fragment emitted in the form of γ -rays ($\sim 3.6 \text{ MeV}$). The fit to the data using Eq.(3.7.) now yields the values of the remaining free parameters θ_f and the overall normalization X given by

$$X = \int dN/dE(E) dE = \alpha_1 + \alpha_2. \quad (3.15)$$

With an allowance of 10% error for each parameter, θ_f is found to be $1.1 \pm 0.1 \text{ MeV}$ yielding a ratio of pre- to post-fission neutrons $\kappa = \alpha_2/\alpha_1 = 0.5 \pm 0.3$, with $\alpha_2 = 2.7 \pm 0.9$ pre- and $\alpha_1 = 5.4 \pm 1.8$ post-fission evaporation neutrons per stopped pion. This ratio κ for pion absorption at rest may be compared with α -induced reactions for ^{238}U at 50 MeV [EdeD79] (0.53 ± 0.15) and 45 MeV [FraM75] (0.8 ± 0.4), where practically the whole kinetic energy of the α -particle is converted to excitation energy, as well as p-induced reactions at 155 MeV [CheF70] (1.1 ± 0.2), where because of elastic scattering only a part of the kinetic energy of the proton is converted to excitation energy. The total number of neutrons emitted per stopped pion is 9.4 ± 1.5 , where the contribution of neutrons emitted with an energy below 1.2 MeV is now estimated by Eq.(3.7). As has already been mentioned using only the evaporation formula Eq.(2.6) with a nuclear "temperature" parameter $\theta = 1.51 \text{ MeV}$ gives essentially the same result 9.6 ± 1.2 (see Tab.1a).

In the model of Kozlowski and Zglinski [KozZ80] the calculated total neutron multiplicity is 10.4 (1.5 nonevaporation, 4.3 pre- and 4.6 post-fission evaporation) neutrons per stopped pion, giving a ratio $\kappa = 0.9$, in agreement with the estimate above.

3.2. NEUTRON AND CHARGED PARTICLE SPECTROSCOPY AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN THE Ni ISOTOPES ^{58}Ni , ^{60}Ni , ^{62}Ni , ^{64}Ni .

The spectra of neutrons and charged particles emitted after the absorption of stopped negative pions in the Ni isotopes were measured in order to obtain information on isotope effects in the yields of the emitted particles. The measured neutron spectra are shown in Fig.15, along with the corresponding extrapolated evaporation fits. A log-log representation was chosen to emphasize the low energy part of the spectra, the high energy part being the same for all four isotopes. The strong isotope dependence of the evaporation neutrons, already mentioned in section 2.2.1. (Fig.5), is very clearly displayed. The extracted nuclear temperature parameters θ are given in Tab.4a for the four Ni isotopes and show no isotope dependence. The errors however are fairly large due to a large amount of neutron background encountered during the measurements because only rather thin Ni targets were available (see section 2.1.3., Fig.4 and section 2.2.1., Fig.5). Neutron multiplicities for the four Ni isotopes are also given in Tab.4a for evaporation and nonevaporation neutrons as well as for neutrons emitted above thresholds of 0, 2 and 20 MeV. The yield of low energy (evaporation) neutrons increases with increasing neutron number N, that of high energy (direct) neutrons is roughly the same for all four isotopes. The mean energies carried away by neutrons per stopped pion and per neutron are contained in Tab.4b for total, evaporation and direct neutrons. Results for ^{59}Co [HarI78] are given for comparison.

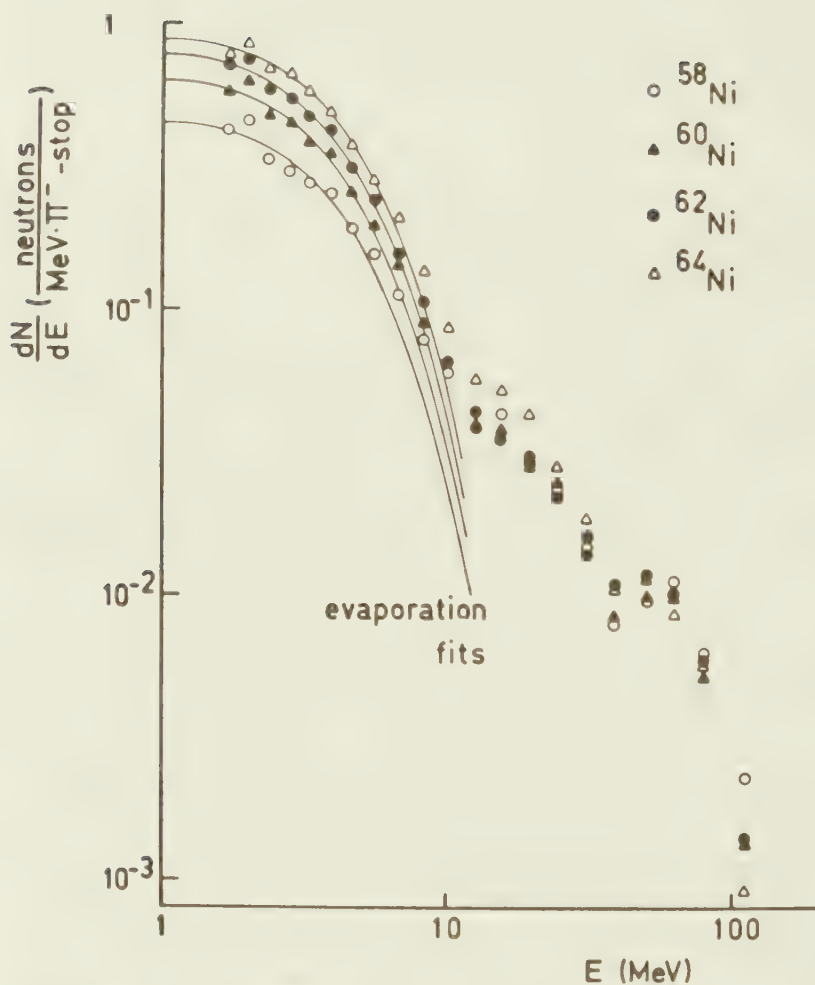


Fig.15/MEASURED NEUTRON ENERGY SPECTRA AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN THE Ni ISOTOPES. The figure shows the measured neutron energy spectra after the absorption of stopped negative pions in the Ni isotopes. The spectra are normalized to the number of stopped pions. The solid lines represent the evaporation fits to the low energy neutrons. The relative errors between the isotopes are 10%, the error in absolute normalization 20%.

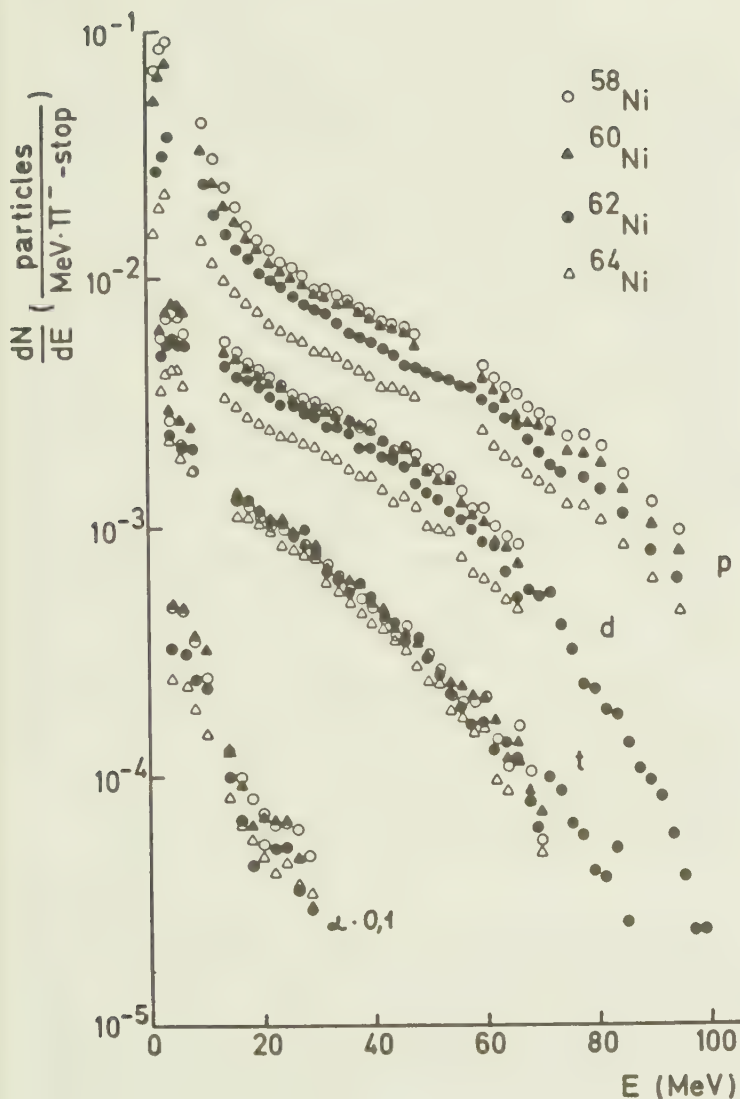


Fig.16/MEASURED CHARGED PARTICLE (p, d, t AND α) ENERGY SPECTRA AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN THE Ni ISOTOPES. The figure shows the measured charged particle (p, d, t and α) energy spectra after the absorption of stopped negative pions in the Ni isotopes. All spectra are normalized to the number of stopped pions. The relative errors between the isotopes are 10% and between the emitted charged particles also 10%. An overall uncertainty in the absolute normalization of 15% must be included for the total error. The d and t spectra for ^{62}Ni extend towards higher energies than for the other isotopes because for this target a second measurement with a thick Ge detector was performed. Note that the alpha spectra are multiplied by a factor of 0.1.

	58Ni	60Ni	62Ni	64Ni	59Co [Har178] [PruE81]	59Co [PruE79]
θ [MeV]	2.3 (2)	2.3 (2)	2.2 (2)	2.4 (2)	2.41	
X_n [n/ π] (0-140)	3.4 (7)	4.1 (8)	4.7 (9)	5.5 (11)	4.1 (2)	
(2-140)	2.6 (5)	2.9 (6)	3.3 (7)	3.9 (8)	3.1	
(20-140)	0.9 (3)	0.8 (2)	0.8 (2)	0.9 (3)	1.1	
X_{nd} [n/ π]	1.3 (4)	1.2 (4)	1.2 (4)	1.4 (4)	1.4 (1)	
X_{ne} [n/ π]	2.1 (6)	2.9 (9)	3.5 (11)	4.1 (12)	2.7	
X_p [p/ π] (2-100)	2.0 (4)	1.6 (3)	1.0 (2)	0.6 (1)	1.1 (2)	
(20-100)	0.41(6)	0.38(6)	0.31(5)	0.22(3)	0.32(4)	
X_d [d/ π] (2-100)	0.29(6)	0.30(6)	0.25(5)	0.17(3)	0.22(4)	
(20-100)	0.13(2)	0.12(2)	0.11(2)	0.08(1)	0.11(2)	
X_t [t/ π] (2- 70)	0.07(2)	0.07(2)	0.07(2)	0.06(2)	0.06(2)	
(20- 70)	.028(4)	.029(4)	.028(4)	.024(4)	.024(4)	
X_α [α / π] (2- 30)	0.36(11)	0.36(11)	0.24(7)	0.18(5)	0.22(7)	
X_c [c/ π] (2-100)	2.7 (5)	2.3 (4)	1.5 (3)	0.97(2)	1.6 (3)	
(20-100)	0.64(10)	0.60(9)	0.50(8)	0.36(5)	0.45(8)	
$\langle n \rangle$ [n/ π] (0-140)	4.6 (9)	5.3 (10)	5.6 (10)	6.2 (10)	4.9 (10)	4.5(2)
$\langle p \rangle$ [p/ π] (2-100)	3.1 (7)	2.7 (7)	1.8 (6)	1.2 (6)	1.8 (6)	1.5(2)
$\langle n \rangle + \langle p \rangle$ [part./ π]	7.7 (11)	8.0 (12)	7.4 (11)	7.4 (11)	6.7 (11)	6.0(3)
$\langle n \rangle - \langle p \rangle$ [part./ π]	1.5 (9)	2.6 (9)	3.8 (10)	5.0 (11)	3.1 (10)	3.0(3)

Tab.4a/RESULTS FROM NEUTRON AND CHARGED PARTICLE SPECTROSCOPY IN Ni ISOTOPES: NUCLEAR TEMPERATURE PARAMETERS AND NEUTRON AND CHARGED PARTICLE MULTIPLICITIES. Nuclear temperature parameters θ , neutron and charged particle multiplicities X from negative pion absorption in Ni isotopes for different energy intervals are compared with earlier results from neutron [Har178] and charged particle [PruE81] spectroscopy in 59Co. The multiplicities for deuterons were extrapolated up to 100 MeV for 58Ni, 60Ni and 64Ni by comparison with 62Ni. The triton multiplicities between 2 and 20 MeV for all Ni isotopes were estimated from the data for 59Co [PruE81]. Symbol definitions are: θ : nuclear temperatures [MeV] extracted between 2 and 4.3 MeV; X_n , X_p , X_d , X_t , X_α , X_c = $X_p + X_d + X_t + X_\alpha$: neutron, proton, deuteron, triton, alpha-particle and sum of all charged particles multiplicities; $\langle n \rangle$ = $X_n + X_d + 2X_t + 2X_\alpha$, $\langle p \rangle$ = $X_p + X_d + X_t + 2X_\alpha$: total mean number of neutrons and protons emitted; $\langle n \rangle + \langle p \rangle$ = $X_n + X_p + 2X_d + 3X_t + 4X_\alpha$, $\langle n \rangle - \langle p \rangle$ = $X_n + X_t - X_p$.

	58Ni	60Ni	62Ni	64Ni	59Co [Har178] [PruE81]
<Ene> [MeV/ π]	7. (2)	10. (3)	11. (4)	14. (4)	9.3
<Ent> [MeV/ π]	58. (17)	54. (16)	56. (17)	63. (19)	75.7
<End> [MeV/ π]	49. (15)	44. (13)	47. (14)	49. (16)	66.4
<Ene>' [MeV/n]	3.3 (3)	3.3 (3)	3.2 (3)	3.5 (4)	3.5
<Ent>' [MeV/n]	17. (13)	13. (3)	12. (2)	11. (2)	18.7
<End>' [MeV/n]	38. (8)	37. (7)	39. (8)	35. (7)	48.1
<Ep> [MeV/ π] (2-100)	28.	24.	18.	12.	17.
(20-100)	16.	15.	12.	8.6	11.
<Ep>' [MeV/p] (2-100)	14.	15.	18.	20.	17.
(20-100)	39.	39.	39.	39.	38.
<Ed> [MeV/ π] (2-100)	5.5	6.0	5.5	3.4	5.5
(20-100)	4.8	4.4	4.1	3.0	3.7
<Ed>' [MeV/d] (2-100)	19.	20.	22.	20.	25.
(20-100)	37.	37.	37.	37.	37.
<Et> [MeV/ π] (2- 70)	1.2	1.2	1.2	1.1	1.3
(20- 70)	1.0	1.0	1.0	0.8	0.8
<Et>' [MeV/t] (2- 70)	17.	17.	17.	18.	21.
(20- 70)	35.	35.	35.	35.	35.
<Ea> [MeV/ π] (2- 30)	3.2	3.2	2.2	1.6	2.8
<Ea>' [MeV/a] (2- 30)	9.	9.	9.	9.	12.
<Ec> [MeV/ π] (2-100)	37.9	34.4	26.9	18.1	26.6
(20-100)	21.8	20.4	17.1	12.4	15.5

Tab.4b/RESULTS FROM NEUTRON AND CHARGED PARTICLE SPECTROSCOPY IN Ni ISOTOPES: MEAN ENERGIES OF NEUTRONS AND CHARGED PARTICLES. Measured mean energies of neutrons and charged particles emitted after stopped negative pion absorption in Ni isotopes are compared with corresponding results for 59Co [Har178], [PruE81]. Symbols are: <Ent>, <Ene>, <End>, <Ent>', <Ene>', <End>': total, evaporation and direct mean neutron energies per stopped pion and per neutron (primed), <Ep>, <Ed>, <Et>, <Ea>, <Ep>', <Ed>', <Et>', <Ea>': mean charged particle energies for p, d, t and α per stopped pion and per particle (primed) for different energy regions. <Ec> is mean energy per stopped pion carried away by all charged particles.

The energy spectra of protons, deuterons, tritons and alpha particles emitted after the absorption of stopped negative pions in the four Ni isotopes are shown in Fig.16. Some data points around 10 and 50 MeV are missing because none of the three evaluation methods (time-of-flight, $\Delta E-E$ or $\Delta E_1 - \Delta E_2$) could be employed in these regions. Charged particle multiplicities for the four Ni isotopes are given in Tab.4a for protons, deuterons, tritons and alpha particles separately and for the sum of all charged particles for thresholds of 2 and 20 MeV. The yields of both low and high energy protons show a large dependence on neutron number N ; deuterons still show a small dependence, whereas tritons and alpha particles show no dependence within the 10% relative normalization errors. The mean energies carried away by the charged particles per stopped pion and per charged particle are given in Tab.4b for thresholds of 2 and 20 MeV. Results for charged particle spectroscopy in ^{59}Co [PruE81] are shown for comparison. Nuclear temperature parameters and neutron multiplicities are given in Tab.5 for $^{\text{nat}}\text{Ni}$, which was calculated from the Ni isotopes assuming 67.8% ^{58}Ni , 26.4% ^{60}Ni , 3.7% ^{62}Ni and 1.0% ^{64}Ni . Also contained in Tab.5 are results from charged particle spectroscopy after the absorption of stopped negative pions in $^{\text{nat}}\text{Ni}$ and calculated results for $^{\text{nat}}\text{Ni}$ assuming the same relative distribution of Ni isotopes as mentioned above. A Comparison of the two results for $^{\text{nat}}\text{Ni}$ shows that the relative normalization was quite good.

Using Eq.(3.1), one can set up the energy balance for stopped negative pion absorption in the Ni isotopes. With $\langle E_n \rangle$ and $\langle E_c \rangle$ from Tab.4b, $\langle E_g \rangle = 7. \text{ MeV}$ $< B = 8.5 \text{ MeV}$ and $\langle E_b \rangle = 8.5$ (6.1, 6.4, 6.3 and 6.5) $\text{MeV} = 52. \pm 11. , 54. \pm 11. , 54. \pm 11. \text{ and } 55. \pm 11. \text{ MeV}$ [this work], [PruE79], [PruE81] per stopped pion for the four Ni isotopes ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni respectively, one gets:

$$E_{\pi} - E_r - B_{\pi} + M(A, Z) - M(A, Z-1) = 137. \text{ MeV} \quad (3.16)$$

$$\langle E_n \rangle + \langle E_c \rangle + \langle E_g \rangle + \langle E_b \rangle = 155. \pm 21. \quad \text{for } {}^{58}\text{Ni}, \quad (3.17)$$

$$149. \pm 20. \quad \text{for } {}^{60}\text{Ni}, \quad (3.18)$$

$$144. \pm 21. \quad \text{for } {}^{62}\text{Ni}, \text{ and } \quad (3.19)$$

$$143. \pm 21. \text{ MeV} \quad \text{for } {}^{64}\text{Ni}. \quad (3.20)$$

The energy balance is fulfilled within the large errors, that come mainly from the large uncertainty in the mean neutron energies. The isotope dependence of the total energy comes from the fact that the high energy neutrons show no dependence in multiplicity, whereas the high energy protons do.

The mean number of neutrons $\langle n \rangle$ and protons $\langle p \rangle$ emitted after negative pion absorption in the Ni isotopes, including neutrons and protons bound in the charged particles d, t and α , are given in Tab.4a, along with the sum $\langle n \rangle + \langle p \rangle$ and difference $\langle n \rangle - \langle p \rangle$. For comparison the results from neutron [HarI78] and charged particle [PruE81] spectroscopy in ${}^{59}\text{Co}$ are also given in Tab.4a. In Fig.17 the measured direct and total neutron and charged particle multiplicities are shown as a function of target isospin $T = (N-Z)/2$. The number of direct neutrons emitted per stopped pion is 1.3 ± 0.4 for all four Ni isotopes, whereas the number of charged particles with an energy higher than 20 MeV decreases linearly as a function of T at a rate of about -0.1 particles per unit of isospin. The total number of neutrons emitted per stopped pion increases linearly as a function of T at a rate of about 0.7 neutrons per unit of isospin; the total number of charged particles emitted decreases linearly at about the same rate. In Fig.18 both $\langle n \rangle + \langle p \rangle$ and $\langle n \rangle - \langle p \rangle$ are plotted as a function of isospin T . $\langle n \rangle + \langle p \rangle$ is seen to be 7.7 ± 1.2 particles per stopped pion for all four Ni isotopes; the asymmetry between emission of neutrons and protons $\langle n \rangle - \langle p \rangle$ increases linearly at a rate of about 1.2 particles per unit of isospin.

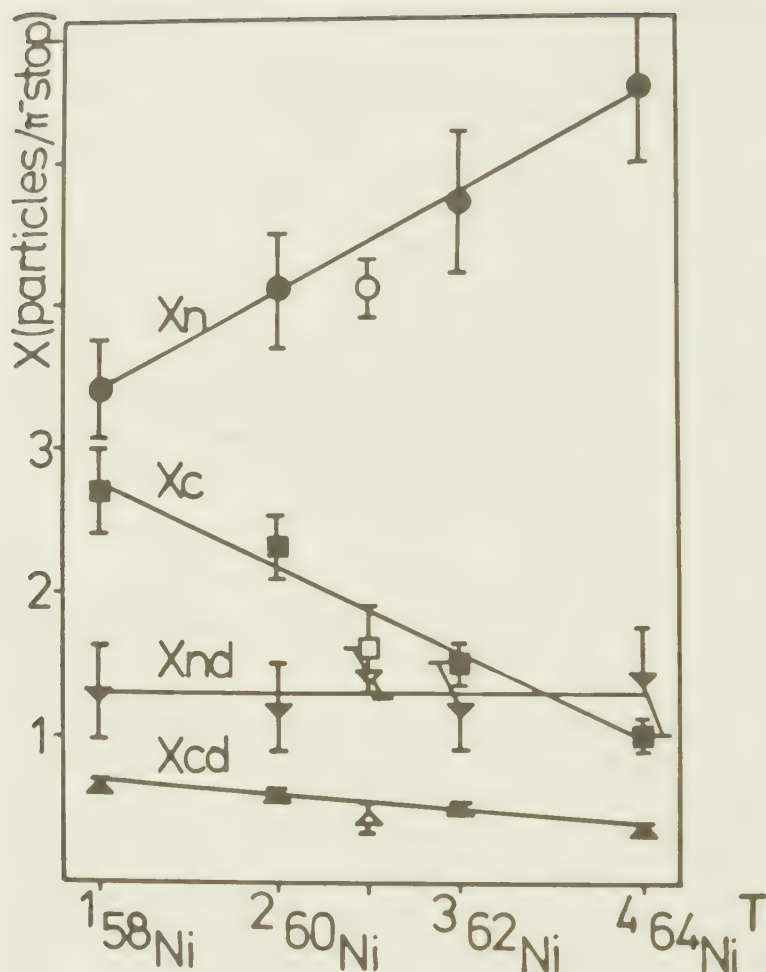


Fig.17/ISOSPIN DEPENDENCE OF NEUTRON AND CHARGED PARTICLE MULTIPLICITIES. Full symbols are measured neutron X_n , X_{nd} and charged particle X_c , X_{cd} multiplicities after negative pion absorption in Ni isotopes as a function of isospin $T = (N-Z)/2$. X_n and X_c are the total neutron and charged particle multiplicities. X_{nd} is the neutron multiplicity for direct (= nonevaporation) neutrons, X_{cd} that for charged particles p, d and t with an energy higher than 20 MeV. Open symbols are from [Har178] and [PrUE81] for ^{59}Co . The errors shown for the four Ni measurements are relative only. An overall absolute error in normalisation of 15% for the charged particles and 20% for the neutrons must be added for the total error.

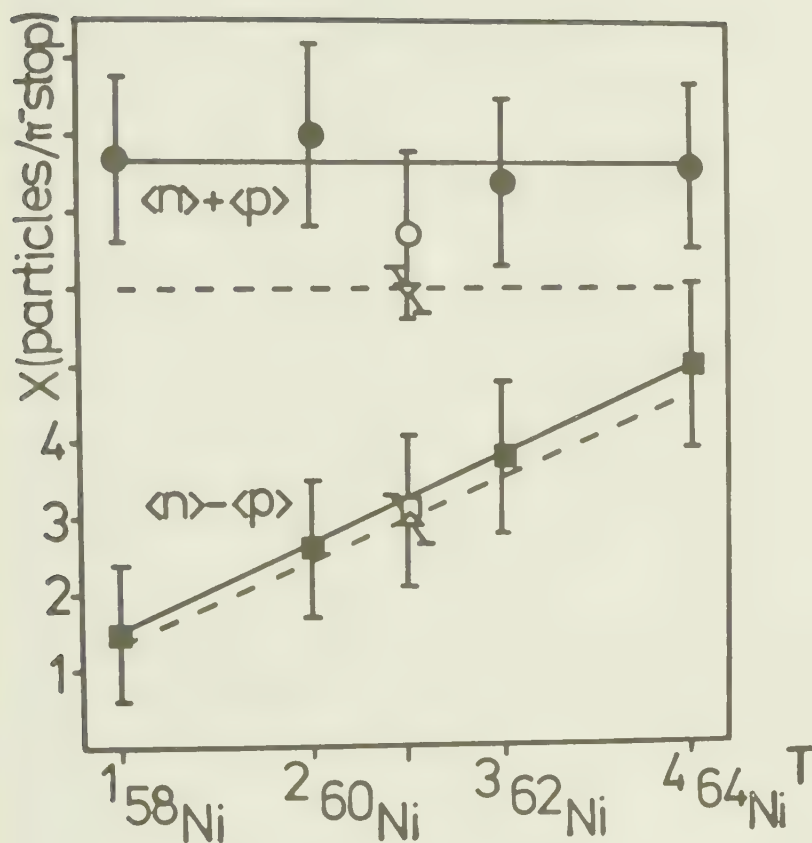


Fig.18/ISOSPIN DEPENDENCE OF MEAN SUM AND DIFFERENCE OF NEUTRONS AND PROTONS EMITTED AFTER THE ABSORPTION OF STOPPED NEGATIVE PIONS IN NI ISOTOPES. Full symbols are measured mean sum $\langle n \rangle + \langle p \rangle$ and difference $\langle n \rangle - \langle p \rangle$ of neutrons and protons emitted (including neutrons and protons bound in the charged particles d, t and α) as a function of isospin $T = (N-Z)/2$. Open symbols are from [HarI78] and [Prue81] for ^{59}Co . The results of the calculations of Kozlowski and Zglinski [KozZ80] given in Tab.5 are shown in the figure as dashed lines.

	natNi measured	natNi computed calc
θ [MeV]		2.3 (2) 2.54
Xn [n/ π] (0-140)		3.7 (7) 3.0
(2-140)		2.7 (5) 2.4
(20-140)		0.9 (3) 0.9
Xnd [n/ π]		1.3 (4) 1.2
Xne [n/ π]		2.4 (7) 1.8
Xp [p/ π] (2-100)		1.8 (4) 1.2
(20-100)	0.39 (6)	0.39 (6) 0.21
Xd [d/ π] (2-100)		0.29 (6) 0.22
(20-100)	0.122(2)	0.13 (2) 0.10
Xt [t/ π] (2- 70)		0.07 (2) 0.04
(20- 70)	0.026(4)	0.028(4) 0.017
Xa [a/ π] (2- 30)		0.26 (6) 0.27

Tab. 5 /NUCLEAR TEMPERATURE PARAMETERS AND NEUTRON AND CHARGED PARTICLE MULTIPLICITIES FOR natNi. Computed results for natNi for both the measured and calculated data (assuming natNi= 67.8% 58Ni+ 26.4% 60Ni+ 3.7% 62Ni+ 1.0% 64Ni) are given, along with directly measured multiplicities from charged particle spectroscopy in natNi. Symbol definitions are as in Fig.4a.

The large isotope effects for the yields of the low energy particles (n, p, d, t and α) can be understood from differences in binding energy. Due to the reduced binding energy of neutrons in heavier Ni isotopes, evaporation becomes more likely. The reverse is true for proton evaporation. The experimental results from negative pion absorption in the Ni isotopes have been interpreted in terms of the same model as in section 3.1.. A comparison of

the same calculations with results from charged particle spectroscopy after negative pion absorption in ^{12}C , ^{59}Co and ^{197}Au is given in [PruE80]. The results of the calculations for the Ni isotopes are given in Tab.6. The overall agreement between measurement and calculation is reasonable; the dependences of neutron and proton multiplicities on isospin T are reproduced by the calculations for low energy neutrons and protons and high energy neutrons, the strong dependence of the high energy protons however is not reproduced. Differences in the ratio R of np to pp pairs in the nucleus from the statistical value $2N/(Z-1)$ used in the calculations could partially explain the large isotope effects for the high energy protons. Although both the mean number of neutrons $\langle n \rangle$ and protons $\langle p \rangle$ and the sum $\langle n \rangle + \langle p \rangle$ are somewhat underestimated by the calculations, the independence of $\langle n \rangle + \langle p \rangle$ and the dependence of $\langle n \rangle - \langle p \rangle$ on isospin T is well reproduced (see Fig.18): $\langle n \rangle - \langle p \rangle = 1.0 \cdot T + 0.5$ as compared with the experimental result $\langle n \rangle - \langle p \rangle = 1.2 \cdot T + 0.3$. This result is in agreement with other stopped pion experiments in the Ni isotopes ^{58}Ni , ^{60}Ni and ^{62}Ni [CasJ77], which quote an increase in $\langle n \rangle - \langle p \rangle$ of 1.1 particles per unit of isospin and with p induced reactions in ^{58}Ni , ^{60}Ni , ^{62}Ni and ^{64}Ni [SadJ77], which give an increase of 1.26 particles per unit of isospin. Both of the above references however obtain somewhat lower results for the sum $\langle n \rangle + \langle p \rangle$, namely about 4 - 6 particles for ^{58}Ni , ^{60}Ni and ^{62}Ni [CasJ77] and about 5 particles for all Ni isotopes [SadJ77]. The dependence of $\langle n \rangle + \langle p \rangle$ on isospin seen by Cassagnou et al. [CasJ77] was not seen in the present work.

Numerical tables of the measured neutron and charged particle spectra are given in Tab.10a-e of the appendix.

	58Ni		60Ni		62Ni		64Ni		59Co	
	measured	calc	measured	calc	measured	calc	measured	calc	measured	calc
θ [MeV]	2.3 (2)	2.54	2.3 (2)	2.55	2.2 (2)	2.49	2.4 (2)	2.46	2.41	2.57
X_n [n/ π] (0-140)	3.4 (7)	2.8	4.1 (8)	3.4	4.7 (9)	4.0	5.5 (11)	4.6	4.1 (2)	3.7
(2-140)	2.6 (5)	2.2	2.9 (6)	2.6	3.3 (7)	3.0	3.9 (8)	3.4	3.1	2.8
(20-140)	0.9 (3)	0.85	0.8 (2)	0.87	0.8 (2)	0.88	0.9 (3)	0.89	1.1	0.90
X_{nd} [n/ π]	1.3 (4)	1.2	1.2 (4)	1.3	1.2 (4)	1.3	1.4 (4)	1.4	1.4 (1)	1.3
X_{ne} [n/ π]	2.1 (6)	1.6	2.9 (9)	2.1	3.5 (11)	2.7	4.1 (12)	3.2	2.7	2.4
X_p [p/ π] (2-100)	2.0 (4)	1.3	1.6 (3)	0.92	1.0 (2)	0.60	0.6 (1)	0.40	1.1 (2)	0.67
(20-100)	0.41(6)	0.22	0.38(6)	0.20	0.31(5)	0.17	0.22(3)	0.15	0.32(4)	0.16
X_d [d/ π] (2-100)	0.29(6)	0.23	0.30(6)	0.21	0.25(5)	0.19	0.17(3)	0.17	0.22(4)	0.19
(20-100)	0.13(2)	0.10	0.12(2)	0.10	0.11(2)	0.09	0.08(1)	0.08	0.11(2)	0.08
X_t [t/ π] (2- 70)	0.07(2)	0.04	0.07(2)	0.05	0.07(2)	0.05	0.06(2)	0.05	0.06(2)	0.05
(20- 70)	.028(4)	0.02	.029(4)	0.02	.028(4)	0.02	.024(4)	0.02	.024(4)	0.02
X_a [a/ π] (2- 30)	0.36(11)	0.27	0.36(11)	0.27	0.24(7)	0.21	0.18(5)	0.14	0.22(7)	0.25
$\langle n \rangle$ [n/ π] (0-140)	4.6 (9)	3.6	5.3 (10)	4.2	5.6 (10)	4.7	6.2 (10)	5.2	4.9 (10)	4.5
$\langle p \rangle$ [p/ π] (2-100)	3.1 (7)	2.1	2.7 (7)	1.7	1.8 (6)	1.2	1.2 (6)	0.90	1.8 (6)	1.4
$\langle n \rangle + \langle p \rangle$ [part./ π]	7.7 (11)	5.7	8.0 (12)	5.9	7.4 (11)	5.9	7.4 (11)	6.1	6.7 (11)	5.9
$\langle n \rangle - \langle p \rangle$ [part./ π]	1.5 (9)	1.5	2.6 (9)	2.5	3.8 (10)	3.5	5.0 (11)	4.3	3.1 (10)	3.1

Tab.6 /COMPARISON OF NUCLEAR TEMPERATURE PARAMETERS AND NEUTRON AND CHARGED PARTICLE MULTIPLICITIES WITH CALCULATIONS. Nuclear temperature parameters θ and neutron and charged particle multiplicities X are compared with the calculations described in the text. Symbol definitions are as in Tab.4a.

3.3. GENERAL CONCLUSIONS ON THE ABSORPTION OF STOPPED NEGATIVE PIONS IN NUCLEI.

In this section some general conclusions on the absorption of stopped negative pions in nuclei will be made. First the ratio R of absorbing np to pp pairs in the nucleus will be discussed. For ^{197}Au and ^{59}Co the statistical ratio R' is about 3.0 and 2.5, respectively. Model dependent values of R can be derived by fitting the experimental data to calculations using R as a free parameter. In Ref. [PruE80] the yields of residual products from the absorption of stopped negative pions in nuclei were compared with calculations of Iljinov et al. [IljN76], Gadioli and Gadioli-Erba [GadG76] and Kozlowski and Zglinski [KozZ80] as a function of R . For ^{197}Au and ^{59}Co lower limits for R were obtained, namely 1.5 and 1.2 respectively. Assuming that all high energy nucleons ($E > 20$ MeV) come directly from pion absorption on an np or a pp pair, the ratio R can be estimated from the yields of high energy neutrons and protons. Using the proton data of Pruys et al. [PruE81] and the present neutron data, one obtains a ratio R of 2.1 ± 0.5 for ^{197}Au (see Tab.7). For the Ni isotopes the estimates for R vary from 0.6 to 1.6. For ^{62}Ni one obtains 0.8 ± 0.3 . Due to final state interactions of the primary nucleons, these estimates are a lower limit only. Using the model of Kozlowski and Zglinski [KozZ80] to calculate the yields of high energy neutrons and protons as a function of R and then comparing with the present experimental yields and those from Ref. [HarI78] and Ref. [PruE81], one obtains the limits $1.2 < R < 3.0$ for ^{197}Au and $R = 1.0$ for ^{59}Co . In conclusion one can say that for ^{197}Au the ratio R is consistent with the statistical value R' . For the Ni isotopes and ^{59}Co [HarI78] the estimates for R are significantly lower than the statistical value. For the Ni isotopes the dependence of R on $N/(Z-1)$ is stronger than one expects from binding energy differences and a $2N/(Z-1)$ dependence alone. Clearly further experimental and theoretical investigations are necessary to understand this behavior. More reliable values of R could be obtained by an accurate measurement of the

neutron and proton spectra at the highest possible energies and by measuring nn and np coincidences directly [HeuE80]

	197Au	197Au [HarI78]	natPb [NorK68]	62Ni	59Co [HarI78]	natCu [NorK68]
$X_n [n/\pi] E > 20. \text{ MeV}$	0.89(14)	0.94(10)		0.9 (3)	1.06(10)	
$X_p [n/\pi] E > 20. \text{ MeV}$	0.17(3)	0.17(3)		0.31(5)	0.30(4)	
$R = 0.5 \cdot (X_n/X_p - 1)$	2.1 (5)	2.3 (6)	4.7(47)	0.8 (3)	1.3 (3)	2.0 (14)
$R' = 2 \cdot R/(R+1)$	3.03	3.03	3.09	2.52	2.46	2.46

Tab.7 /RATIO R OF ABSORBING NP TO PP PAIRS. The table contains the measured neutron [this work] and proton [PruE80] multiplicities above 20 MeV for 197Au [this work], 197Au [HarI78], 62Ni [this work] and 59Co [HarI78], the deduced ratio R from the experimental data, assuming that all high energy protons and neutrons come directly from pion absorption on a np or pp pair and for comparison the statistical ratio R'. Due to final state interactions the given values of R are lower limits only.

The importance of pion absorption on heavier clusters in nuclei will be discussed below. Experimental and theoretical investigations support the two nucleon absorption model, whereas pion absorption on four nucleon clusters seems to be of minor importance [Huef75], [Walt77]. A recent calculation [BerR78] of pion absorption rates in light nuclei shows that at most 10 to 20% of the absorption could be explained by mechanisms involving more than two nucleons. By measuring neutron-triton coincidences after pion absorption in ^{12}C an estimate of $> 4.6\%$ per stopped pion of the amount of four nucleon absorption was obtained by Lee et al. [LeeM72]. Assuming the same ratios for the absorption of stopped negative pions on alpha clusters in nuclei as for stopped pion absorption in ^4He , one can derive some upper limits from the experimental data. In Ref. [PruE80] the calculations of Iljinov et al. [IljN76] for pion absorption on a quasi-deuteron and on a quasi-alpha

were used to fit the experimental yields of residual products from stopped pion absorption in nuclei. An upper limit of 30% for the probability of π^- -absorption was obtained for ^{197}Au and ^{209}Bi . The yields of tritons emitted after the absorption of stopped negative pions can also be used to give an upper limit for the amount of alpha absorption. Taking the triton data from Ref. [PruE81], one obtains an upper limit for the amount of alpha absorption of about 25% for ^{197}Au and 28% for ^{59}Co . The neutron spectra of Kozlowski and Zglinski [KozZ80] were used to obtain an upper limit for pion absorption on an alpha cluster by fitting different energy regions of the neutron spectrum of ^{197}Au with different contributions of alpha absorption. In Fig.13 the measured spectrum of neutrons emitted after the absorption of stopped negative pions in ^{197}Au is shown together with the calculations of Kozlowski and Zglinski [KozZ80] for no alpha absorption, 30% and 100% alpha absorption. Considering the slopes of the low energy part of the neutron spectrum, the measured nuclear temperature parameter allows at most a 20% contribution within the experimental error ($\theta_{\text{exp}} = 1.47 \pm 0.07 \text{ MeV}$, $\theta_{\text{calc}}[\alpha=0\%] = 1.47 \text{ MeV}$, $\theta_{\text{calc}}[\alpha=20\%] = 1.54 \text{ MeV}$, $\theta_{\text{calc}}[\alpha=100\%] = 1.67 \text{ MeV}$). Taking the high energy region from 12 to 130 MeV and fitting the absolute magnitude and spectral shape, one obtains an upper limit of about 25% alpha absorption within an absolute error in normalisation of 15%. It can be concluded that the measured neutron spectra are in agreement with pion absorption on a nucleon pair. No pion absorption on an alpha cluster is needed to explain the data. However a contribution of up to about 25% cannot be excluded.

SUMMARY. In summary one can say that the inclusive neutron spectra after the absorption of stopped negative pions in heavy nuclei can be explained by the absorption on two peripheral nucleons, using the statistical ratio R' of absorbing np to pp pairs. For the Ni isotopes the extracted ratio R is close to 1. For the nuclei investigated the contribution from pion absorption on heavier clusters is less than 25%. The pre-equilibrium decay of the nucleus makes an important contribution to the spectra. Finally the evaporation neutrons demonstrate the lack of shell effects in the nuclear level density parameters in the compound nuclear excitation region sampled by the stopped pion reaction. For ^{238}U the ratio of pre- to post fission neutrons was found to be about 0.5 ± 0.3 .

NOTE ADDED IN PROOF. The charged particle data from this work were absolutely normalized to the charged particle data of Ref. [PruE81]. In a paper to be published on pion absorption in Ni isotopes, the absolute normalization of Ref. [HeuE80] and Ref. [Senn81], which is 10% lower than that of Ref. [PruE81], will be used.

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6. APPENDIX.

6.1. EXPERIMENTAL DETAILS.

Fig.19a gives the relation between proton recoil energy and electron energy for equal light output in a liquid organic scintillator of type NE213. In Fig.19b the energy calibration of the neutron detector NE1 is shown. The off-line neutron detection threshold of 1.0 MeV neutron energy corresponds to 0.184 MeV electron energy or channel 160 of the PH ADC. The walk function for the low and high dynamic range of the neutron detector NE1 for ^{181}Ta is given in Fig.20. The time calibration of the TOF ADC was performed with an ORTEC 462 time calibrator and found to be 11.8 channels per ns for the full 4096 channel TOF spectrum. The time resolution of 1.2 ns (corresponding to 14.2 channels) was obtained from the FWHM of the prompt γ -peak in the γ -TOF spectrum. The neutron detection efficiency for a neutron threshold of 1.0 MeV is shown in Fig.21. A cross section of a neutron detector, containing a liquid organic scintillator NE213, a photomultiplier XP 2041 and the mounting is shown in Fig.22. Fig.23 gives a top view and a cross section of the apparatus used in the charged particle measurements.

6.2. RESULTS AND NUMERICAL TABLES.

In Fig.24 the ^{197}Au neutron data of Hartmann et al. [HarI78] is compared with the data from this work. Fig.25a-c show the A-dependence of the nuclear temperature parameter, the total and direct neutron multiplicities and the the mean evaporation and direct energies emitted per stopped pion. The neutron data are taken from Ref. [AndH64], [VenF64], [HatM65], [HarI78], [KleB79], [this work]. Data for the total neutron multiplicity obtained from emulsion studies and γ -ray activation measurements [TonE52], [SugL52], [Wins53], [TurN53], [TurF53], [Russ56], [CasJ76], [BeeB78], [PruE79] are also plotted. For the data from Ref. [TonE52] a

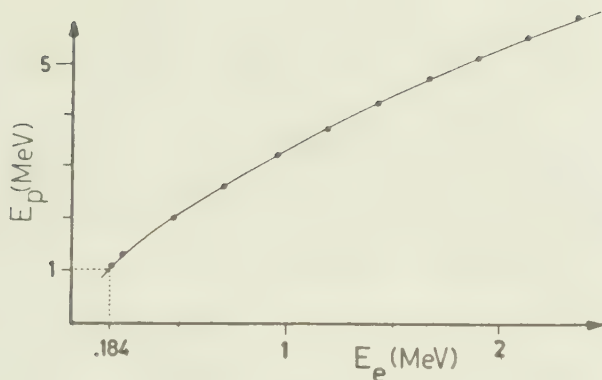


Fig.19a/RELATION BETWEEN PROTON RECOIL ENERGY AND ELECTRON ENERGY FOR EQUAL LIGHT OUTPUT IN NE213. Proton recoil energy E_p is plotted as a function of the corresponding electron energy E_e for equal light output in the liquid organic scintillator NE213. The data is taken from [Dros72], the solid line is an empirical relation between E_p and E_e . The off-line neutron threshold of 1.0 MeV is seen to correspond to an electron energy of 0.184 MeV.

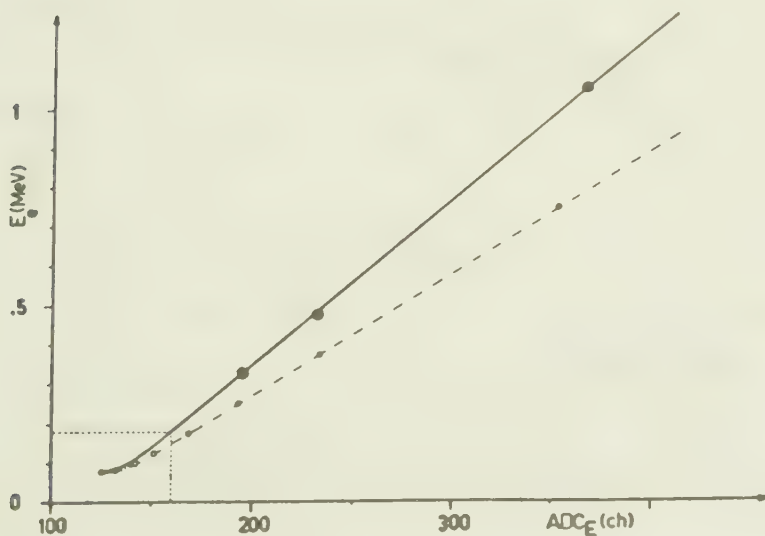


Fig.19b/ENERGY CALIBRATION. The energy calibration (full line) with the radioactive gamma sources ^{22}Na and ^{137}Cs is shown for the neutron detector NE1. The linearity of the PH ADC was tested with a signal generator (dot-dashed line) and was seen to be good down to about 0.1 MeV electron energy. The off-line neutron detection threshold was set at 1.0 MeV neutron energy corresponding to 0.184 MeV electron energy or channel 160 of the PH ADC.

contribution of 1.0 neutron per stopped pion above 15 MeV was added. In Tab.8a and Tab.8b present results from neutron and charged particle spectroscopy after stopped negative pion absorption in nuclei are compared with earlier results. Tab.9 and Tab.10a/b/c/d/e contain the measured neutron and charged particle spectra after the absorption of stopped negative pions in heavy nuclei and Ni isotopes.

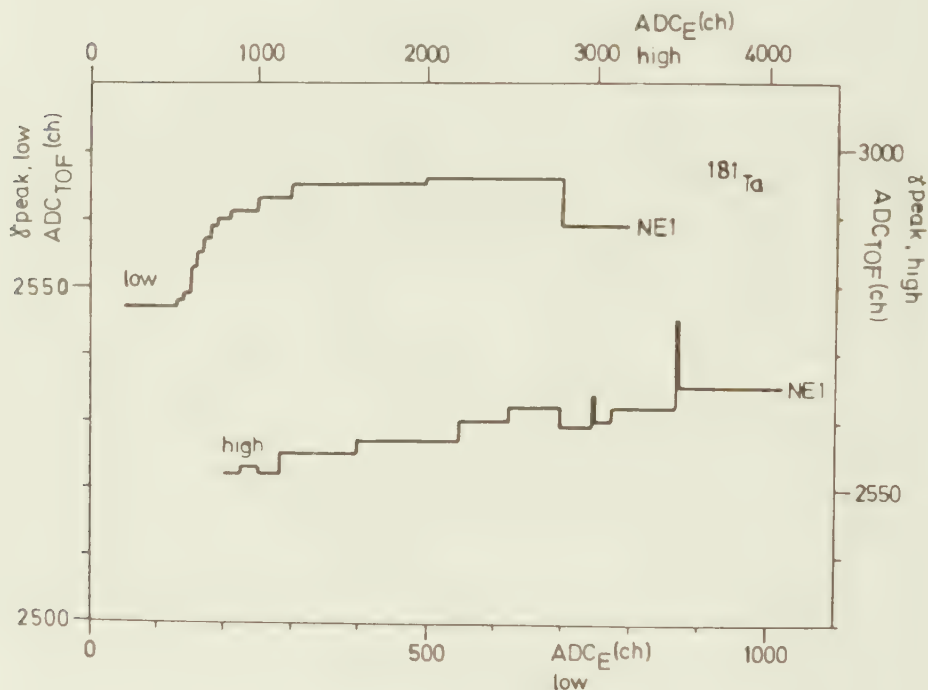


Fig.20/WALK FUNCTION. The position of the prompt gamma peak in the γ -TOF spectrum of ^{181}Ta is shown as a function of 16 successive pulse height intervals for both the low and the high dynamic range of the neutron detector NE1. The walk functions for the other neutron detectors and for the other targets look similar. The time calibration for the TOF ADC was 11.8 channels per ns for the full 4096 channel spectrum.

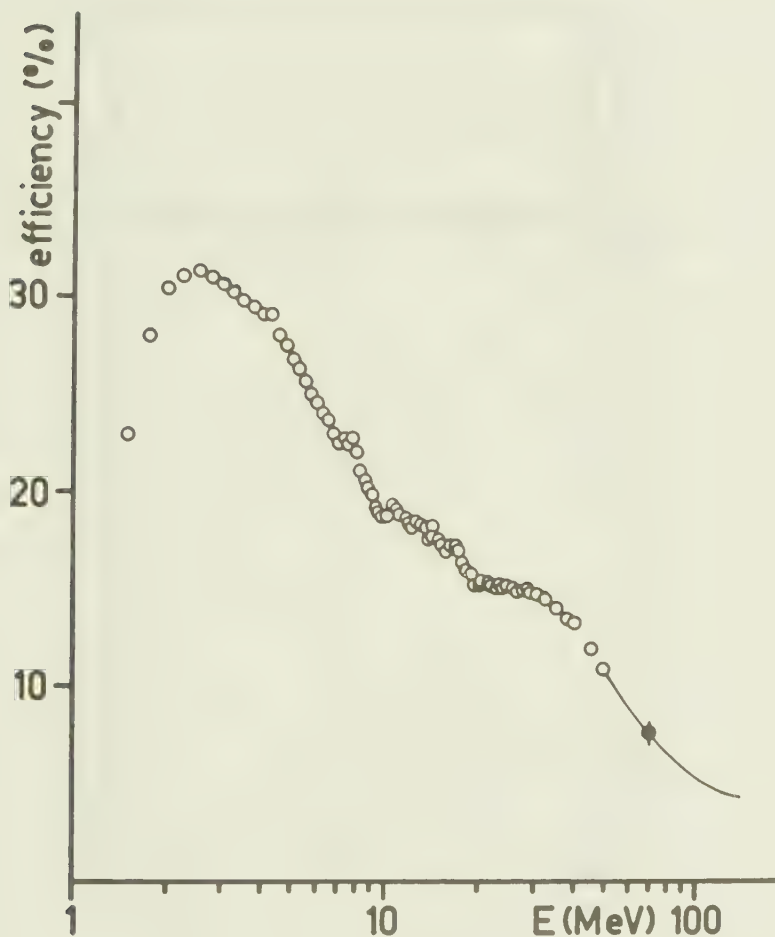


Fig.21/NEUTRON DETECTION EFFICIENCY. The figure shows the neutron detection efficiency for a 2" thick and 5" diameter neutron detector of type NE213 for a neutron threshold of 1.0 MeV. Open circles are calculated points (OakRidge Code 05-S). The solid line is an extrapolation taking into account one measured value at 70 MeV.

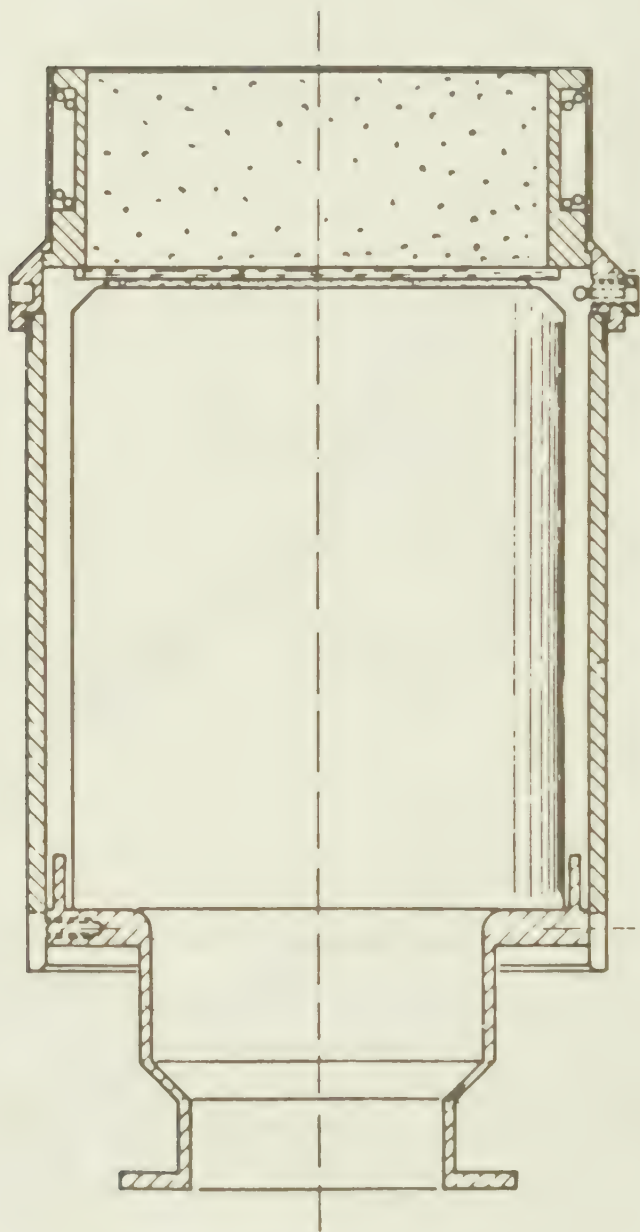
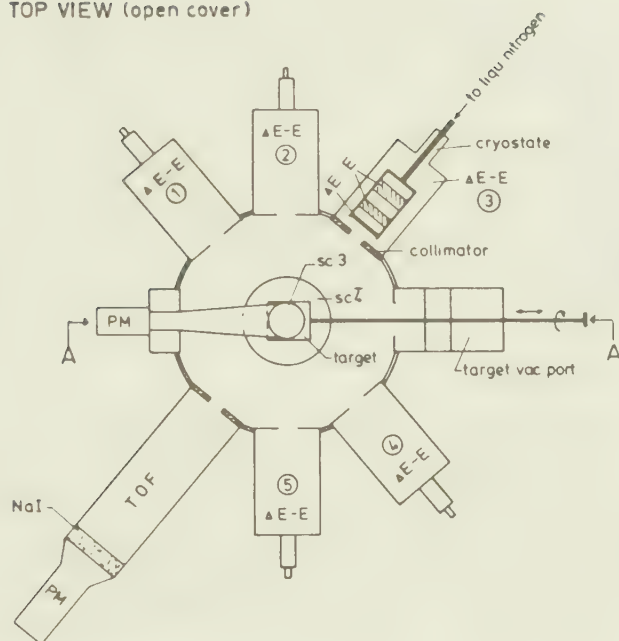


Fig.22/NEUTRON DETECTOR. The figure shows a neutron detector with scintillator, photo-multiplier and mounting.

TOP VIEW (open cover)



CROSS SECT. A-A

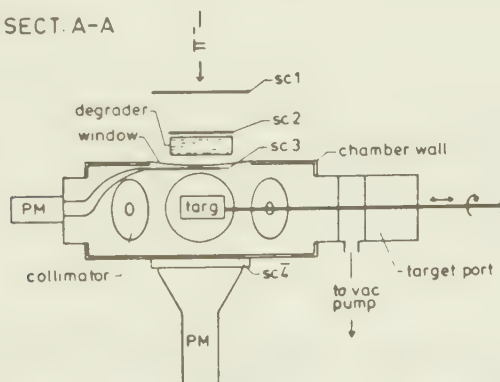


Fig.23/CHARGED PARTICLE DETECTOR ARRANGEMENT. The figure gives a top view and a cross section of the apparatus, which was used to measure charged particles.

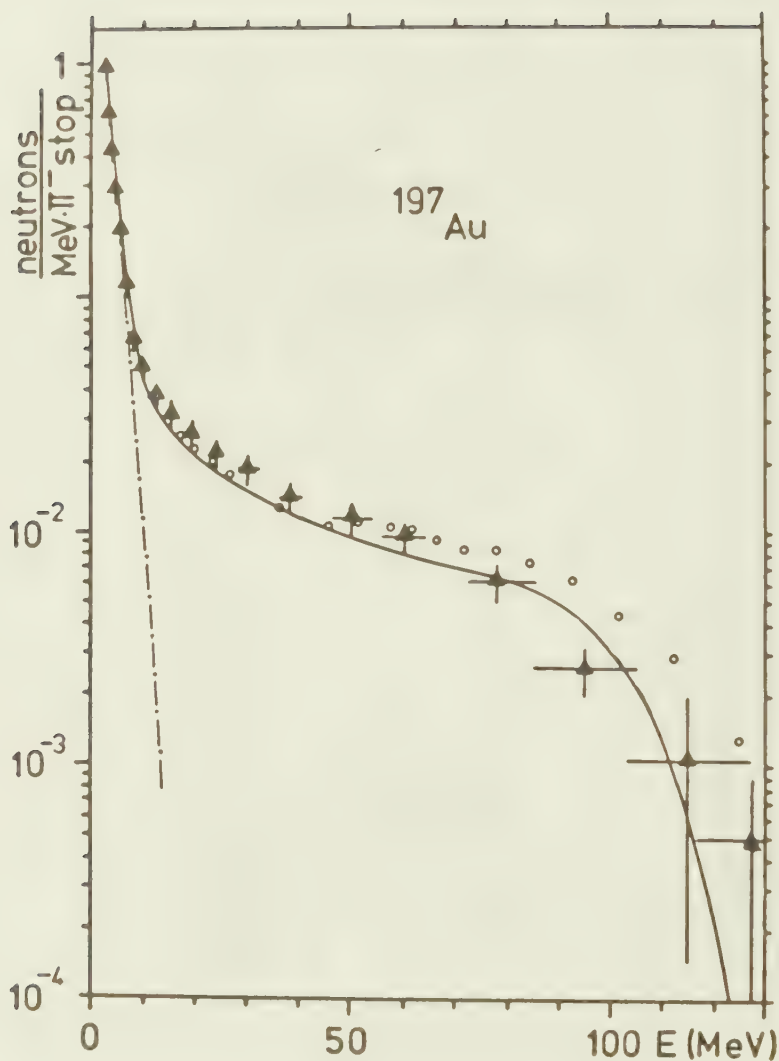


Fig.24/COMPARISON OF NEUTRON SPECTRA FOR ^{197}Au FROM [this work] AND [HarI78]. Same as Fig.14. The open circles represent the data points from [HarI78], which tend to lie higher than the corresponding data points from [this work] in the energy region above about 50 MeV.

Fig.25 /A-DEPENDENCE OF NUCLEAR TEMPERATURE, NEUTRON MULTIPLICITY AND MEAN ENERGY PER STOPPED PION. Symbol definitions are as follows:

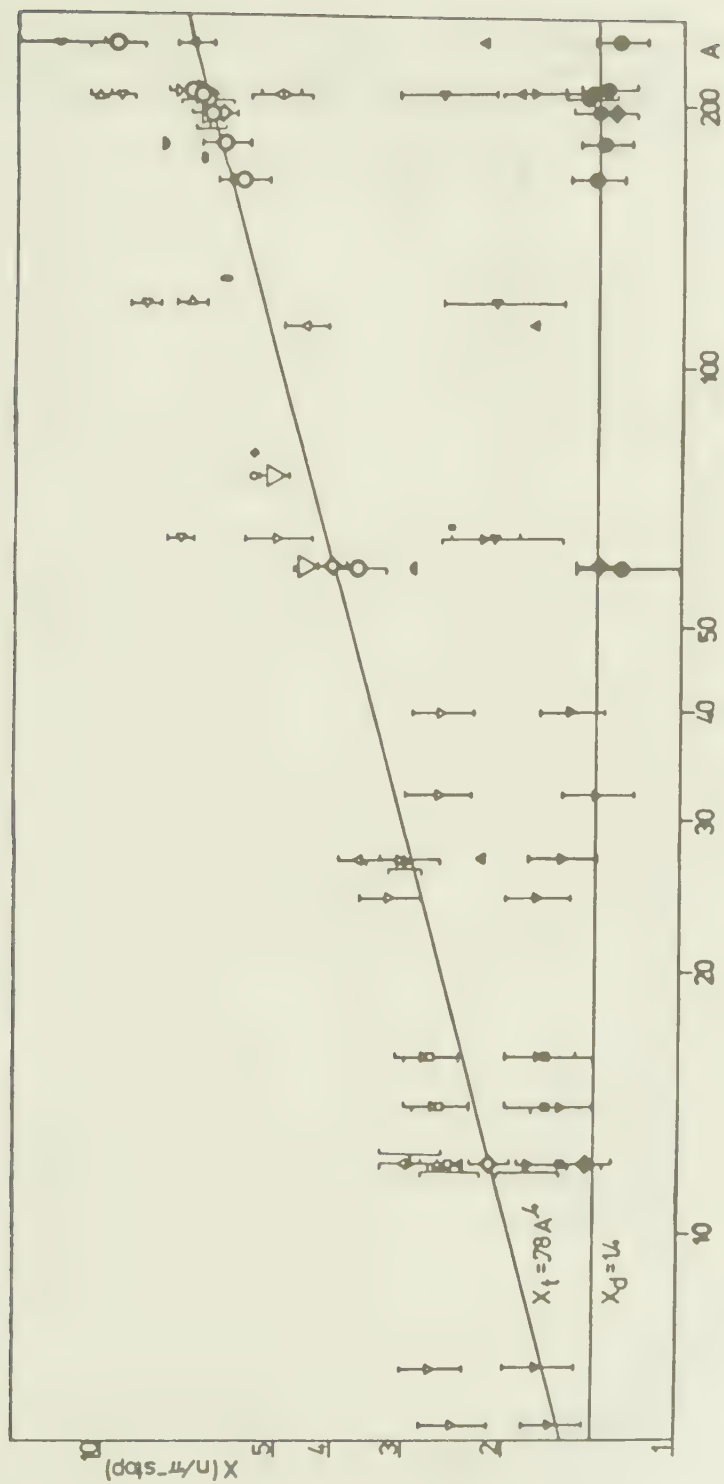
[TonE52]	[▷]	[SugL52]	[◊]	[Wins53]	[○]
[TurN53]	[◉]	[TurF53]	[◻]	[Russ56]	[◐]
[AndH64]	[△]	[VenF64]	[◄]	[HatM65]	[▽]
[EbeA75]	[◌]	[CasJ76]	[◐]	[BeeB78]	[◑]
[HarI78]	[◈]	[PruE79]	[▽]	[KleB79]	[◻]
[this work]	[◉]				

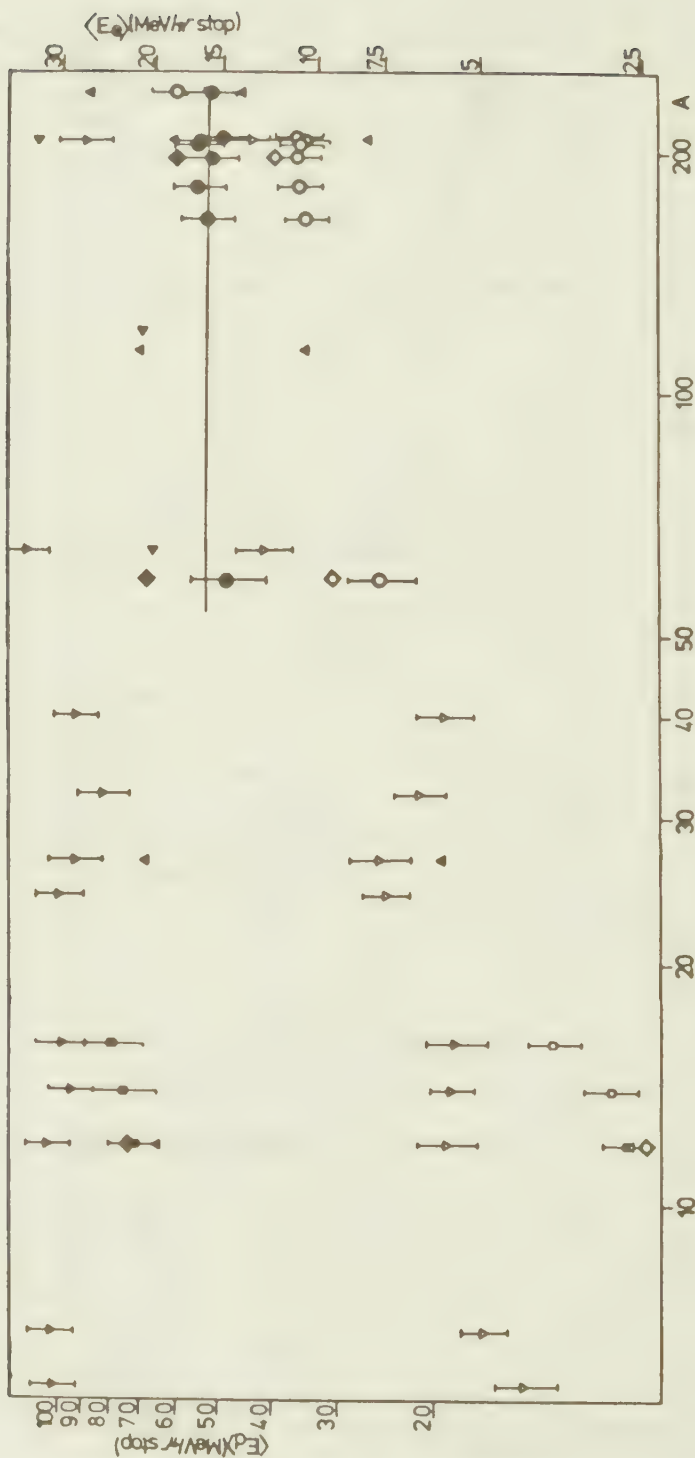
Fig.25a/A-DEPENDENCE OF NUCLEAR TEMPERATURE PARAMETERS. The nuclear temperature parameters θ were extracted from a fit to the experimental data of the form $dN/dE \sim E^{5/11} \cdot \exp(-E/\theta)$. The nuclear temperature T of the residual nucleus after emission of the first evaporation neutron is $T = \theta^{12/11}$. There are 2 sets of experimental data. The first set corresponds to an evaporation fit in the energy region of from about 2 to 5 MeV [AndH64], [HarI78], [KleB79], [this work]. The second set uses a fit region of from about 2 to 15 MeV [VenF64], [HatM65]. Due to precompound neutrons in the region between 5 and 15 MeV, the temperatures from this set of experiments tend to lie higher than those from the first set.

Fig.25b/A-DEPENDENCE OF NEUTRON MULTIPLICITY. Shown in the figure are the total neutron multiplicity X_t (represented by opensymbols) and the non-evaporation (direct) neutron multiplicity X_d (represented by full symbols), $X_d = X_t - X_e$, where X_e is the evaporation multiplicity. [TonE52], [SugL52], [Wins53], [TurN53], [TurF53], [Russ56], [AndH64], [VenF64], [HatM65], [EbeA75], [CasJ76], [BeeB78], [HarI78], [PruE79], [KleB79], [this work]. The solid lines show the trend suggested by the data from [this work]: $X_d = 1.4$ and $X_t = 0.78 \cdot A^{0.4}$ neutrons per stopped pion.

Fig.25c/A-DEPENDENCE OF MEAN ENERGY PER STOPPED PION. Shown in the figure are the mean evaporation neutron energy $\langle E_e \rangle$ (represented by open symbols) and the mean direct neutron energy $\langle E_d \rangle$ per stopped pion (represented by full symbols) [AndH64], [VenF64], [HatM65], [HarI78], [KleB79], [this work]. The total mean neutron energy per stopped pion is given $\langle E_t \rangle = \langle E_d \rangle + \langle E_e \rangle$. The corresponding mean energies per emitted neutron $\langle E_i \rangle$ are given by $\langle E_i \rangle = \langle E_i \rangle / X_i$, $i=t,d,e$, X_i are the neutron multiplicities.







Tab.8a/A COMPARISON OF RESULTS [NEUTRON MULTIPLICITIES, MEAN ENERGIES AND NUCLEAR TEMPERATURE PARAMETERS] FROM NEUTRON SPECTROSCOPY AFTER STOPPED NEGATIVE PION ABSORPTION IN NUCLEI. The results from neutron spectroscopy from [this work] are compared with earlier measurements [AndH64, VenF64, HatM65, KleB79, Isaa76, DeyI76, Hari78]. Symbol definitions are as in Tab.1a/b.

[AndH64]: H.L.Anderson et al., Phys. Rev. 133B (1964) 392 Measured neutron energy/evaporation fit interval: 1.76 - 152. MeV/ 1.76 - 4.02 MeV TOP distance/ time resolution: 1.083 m/ 4 ns FWHM												
En>	$\bar{X}_m$ [n]	$\bar{X}_e$ [n]	$\bar{X}_d$ [n]	$\langle E_T \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	θ [MeV/n]	τ [MeV]		
12C	2.8(3)	3.0	0.6	2.4	68.	2.7	65.	23.	4.5	27.	3.1	3.4
ZrAl	3.2(3)	3.6	1.4	2.2	74.	5.9	68.	21.	4.2	31.	2.9	3.2
natPu	3.5(4)	4.5	2.7	1.8	80.	10.5	69.	18.	3.9	30.	2.7	2.9
238U	5.0(5)	7.0	3.1	1.9	69.	7.8	61.	14.	2.5	32.	1.7	1.9
		7.0	4.6	2.2	100.	13.9	86.	14.	2.9	39.	2.0	2.2
[VenF64]: G.Campos Venuti et al., Phys. Lett. 9 (1964) 45; Nuovo Cim. 34 (1964) 1446 Measured neutron energy/evaporation fit interval: 1. - 50. MeV/ 2. - 15. MeV TOP distance/ time resolution: 1.5 m/ 1.6 ns FWHM												
En>	$\bar{X}_m$ [n]	$\bar{X}_e$ [n]	$\bar{X}_d$ [n]	$\langle E_T \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	θ [MeV/n]	τ [MeV]		
natCu	7.4(4)	5.3(3)	2.1(5)	52.	20.	32.	7.0	3.8	15.0	2.6	2.8(1)	
natNi	8.5(5)	6.4(3)	2.1(5)	52.	21.	31.	6.1	3.3	15.0	2.3	2.5(1)	
natPb	9.4(5)	6.8(3)	2.6(5)	52.	33.	19.	5.5	4.9	7.3	3.4	3.7(1)	
[HatM65]: P.M.Hattersley et al., Nucl. Phys. 67 (1965) 309 Measured neutron energy/evaporation fit interval: 2.5 - 130. MeV/ 3. - 12. MeV TOP distance/ time resolution: 2.0 m/ 2.4 ns FWHM												
En>	$\bar{X}_m$ [n]	$\bar{X}_e$ [n]	$\bar{X}_d$ [n]	$\langle E_T \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	θ [MeV/n]	τ [MeV]		
6Li	2.34(32)	0.74(11)	2.45(32)	0.79	1.66(21)	106.(10)	4.21(50)	102.(10)	43.	5.3	64.	7.65(50)
9Li	2.72(32)	0.70(11)	2.69(34)	0.94	1.75(23)	108.(10)	5.00(50)	103.(10)	40.	5.3	59.	6.60(29)
12Li	2.45(32)	0.61(10)	2.92(36)	1.09	1.83(23)	110.(11)	5.84(70)	103.(10)	36.	5.4	60.	6.68(57)
14B	2.45(32)	0.61(10)	2.52(32)	1.05	1.60(21)	100.(10)	5.73(50)	94.(9)	30.	5.5	63.	6.44(39)
16O	2.59(32)	0.65(10)	2.59(32)	1.42	1.74(24)	105.(12)	5.62(80)	98.(11)	30.	5.5	60.	6.19(46)
natMg	2.90(36)	0.62(10)	3.19(40)	1.42	1.74(24)	105.(12)	5.62(80)	98.(11)	30.	5.5	59.	5.98(69)
ZrAl	2.73(37)	0.62(9)	3.07(42)	1.47	1.60(23)	100.(12)	7.46(100)	92.(11)	33.	2.2	63.	5.25(18)
32S	2.33(30)	0.52(9)	2.63(34)	1.23	1.40(19)	87.(10)	6.44(80)	81.(9)	32.	5.6	58.	5.16(29)
40Ca	2.39(30)	0.64(10)	2.60(32)	1.05	1.55(21)	97.(10)	5.84(80)	91.(9)	37.	5.6	58.	5.28(10)
natU	4.02(50)	0.66(12)	5.03(62)	2.84	2.19(30)	123.(12)	12.4(15)	111.(11)	24.	4.4	51.	3.2(13)
natPu	3.74(44)	0.51(8)	4.98(58)	3.17	1.81(23)	100.(12)	13.2(15)	87.(10)	20.	4.2	48.	2.95(19)
[KleB79]: U.Klein et al., Nucl. Phys. A329 (1979) 339 Measured neutron energy/evaporation fit interval: 2.5 - 140. MeV/ 2.5 - 5.5 MeV TOP distance/ time resolution: 0.825 - 1.26 m												
En>	$\bar{X}_m$ [n]	$\bar{X}_e$ [n]	$\bar{X}_d$ [n]	$\langle E_T \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	$\langle E_B \rangle$ [MeV/n]	$\langle E_D \rangle$ [MeV/n]	θ [MeV/n]	τ [MeV]		
12C	2.5(3)	0.93(8)	1.6(3)	76.(9)	2.7(3)	73.(9)	30.	3.3	46.	2.4	2.6(3)	
14N	2.6(3)	0.90(9)	1.7(3)	78.(10)	2.9(3)	75.(10)	30.	3.2	44.	2.4	2.6(3)	
16O	2.7(3)	0.99(10)	1.7(3)	79.(10)	3.7(4)	79.(10)	29.	3.7	44.	2.6	2.8(3)	

Tab.8b/A COMPARISON OF RESULTS [CHARGED PARTICLE MULTIPLICITIES, AND MEAN ENERGIES] FROM CHARGED PARTICLE SPECTROSCOPY AFTER STOPPED NEGATIVE PION ABSORPTION IN NUCLEI. The results from charged particle spectroscopy from [this work] are compared with earlier measurements [CasC71, SchC79, MecR79, PruE81]. Symbol definitions are as in Fig.4a/b.

[CasC71]: P.J.Castleberry et al., Phys. Lett. 348 (1971) 57, P.J.Castleberry, Ph.D. thesis, Virginia (1971)
Measured particle energy intervals: p: > 6.1 MeV, d: > 7.9 MeV, t: > 9.2 MeV

particle	X _m	[$\frac{g}{\pi}$]	
		$\frac{g}{\pi}$	π
Ep>	6.1 MeV	7.9	MeV
Ed>	7.9 MeV	9.2	MeV
Et>	9.2 MeV		
6Li		14.5(24)	
	p	29.7(41)	
	d	19.1(32)	
7Li		12.4(12)	
	p	19.6(19)	
	d	24.3(24)	
9Be		19.5(33)	
	p	23.4(39)	
	d	12.6(21)	
10B		30.6(45)	
	p	24.4(36)	
	d	10.9(16)	
12C		32.3(67)	
	p	23.0(15)	
	d	10.1(21)	
16O		32.3(31)	
	p	17.9(17)	
	d	4.5(4)	
natN		38.7(48)	
	p	16.4(20)	
	d	4.9(6)	
32S		35.1(36)	
	p	10.3(11)	
	d	2.1(2)	
40Ca		48.5(55)	
	p	13.0(15)	
	d	2.5(3)	
59Co		25.4(23)	
	p	8.1(7)	
	d	1.5(1)	
natPb		8.3(10)	
	p	3.0(3)	
	d	1.1(1)	

Tab.9 /NUMERICAL TABLES OF MEASURED NEUTRON SPECTRA AFTER STOPPED NEGATIVE PION ABSORPTION IN HEAVY NUCLEI. Symbol definitions are: E the neutron energy, $s(E)$ the energy resolution, E_u , E_l the energies corresponding to the upper and lower ends of the TOF bin, $dE = E_u - E_l$. The errors given are statistical only. An overall error in absolute normalisation of 15% must be added for the total error. θ is the nuclear temperature parameter, which was extracted from a fit of the form $dN/dE(E) = Y \cdot E^{-5/11} \cdot \exp(-E/\theta)$ to the low energy neutrons.

E [MeV]	s(E) [MeV]	E_u [MeV]	E_l [MeV]	dE [MeV]	^{165}Ho $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]	^{181}Ta $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]	^{197}Au $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]	^{nat}Tl $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]	^{nat}Pb $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]	^{209}Bi $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]	^{238}U $dN/dE(E)$ [$\frac{1}{\text{s n/}\pi}$]
128.3	13.7	140.3	124.7	15.6	< 0.03	0.05 (3)	0.05 (4)	< 0.02	0.02 (2)	< 0.04	0.10 (4)
114.7	11.5	124.7	106.0	18.7	0.06 (5)	0.17 (3)	0.11 (4)	0.06 (3)	0.16 (3)	0.14 (3)	0.13 (3)
93.5	8.4	106.0	87.1	18.8	0.24 (4)	0.39 (3)	0.26 (3)	0.32 (3)	0.33 (3)	0.28 (3)	0.35 (3)
77.9	6.4	87.1	70.1	17.0	0.68 (4)	0.70 (2)	0.63 (2)	0.71 (3)	0.70 (3)	0.66 (3)	0.68 (3)
61.1	4.4	70.1	55.7	14.4	1.03 (5)	0.97 (2)	0.96 (2)	1.08 (3)	1.03 (3)	0.89 (4)	0.87 (3)
49.3	3.2	55.7	43.9	11.7	1.27 (5)	1.10 (3)	1.16 (2)	1.30 (3)	1.21 (3)	1.10 (4)	1.09 (4)
39.3	2.2	43.9	34.6	9.3	1.60 (5)	1.31 (3)	1.40 (3)	1.50 (3)	1.44 (3)	1.29 (4)	1.35 (4)
30.6	1.6	34.6	27.3	7.3	2.02 (6)	1.69 (3)	1.83 (3)	1.79 (4)	1.71 (4)	1.66 (5)	1.55 (5)
24.0	1.2	27.3	21.7	5.7	2.24 (8)	2.01 (5)	2.16 (4)	2.35 (6)	2.16 (5)	1.98 (7)	1.86 (6)
19.3	0.9	21.7	17.3	4.4	2.80 (11)	2.51 (6)	2.59 (6)	2.80 (8)	2.46 (7)	2.33 (9)	2.45 (8)
15.3	0.6	17.3	13.8	3.4	3.02 (14)	3.06 (7)	3.17 (7)	3.23 (9)	3.10 (9)	2.96 (11)	2.84 (10)
12.4	0.5	13.8	11.2	2.7	4.28 (17)	3.59 (9)	3.79 (8)	3.87 (11)	3.71 (10)	3.50 (14)	3.40 (13)
9.96	0.36	11.2	9.07	2.09	5.26 (22)	4.92 (12)	5.06 (11)	4.74 (15)	4.63 (13)	4.57 (18)	5.28 (16)
8.19	0.28	9.07	7.43	1.65	6.84 (26)	6.87 (14)	6.65 (13)	6.09 (17)	5.90 (16)	5.90 (21)	8.30 (19)
6.69	0.22	7.43	6.12	1.31	13.0 (3)	12.1 (2)	11.7 (2)	10.7 (2)	9.9 (2)	10.2 (3)	17.0 (2)
5.56	0.18	6.12	5.08	1.04	19.5 (3)	19.3 (2)	19.6 (2)	18.4 (2)	16.8 (2)	17.5 (3)	30.5 (3)
4.61	0.14	5.08	4.24	0.84	29.0 (4)	29.6 (2)	29.4 (2)	28.5 (3)	26.4 (3)	27.3 (3)	49.1 (3)
3.88	0.12	4.24	3.56	0.68	41.7 (5)	42.7 (3)	42.5 (3)	41.8 (3)	40.3 (3)	40.7 (4)	72.0 (4)
3.26	0.09	3.56	3.01	0.55	56.4 (6)	60.3 (4)	61.2 (3)	60.0 (4)	58.9 (4)	61.2 (5)	100.5 (5)
2.77	0.08	3.01	2.56	0.45	69.4 (7)	76.3 (4)	77.7 (4)	79.4 (5)	78.9 (5)	83.2 (6)	128.7 (6)
2.36	0.07	2.56	2.19	0.37	82.8 (9)	91.0 (5)	96.2 (5)	97.6 (6)	99.8 (6)	104.6 (8)	156.7 (8)
2.03	0.06	2.19	1.88	0.31	96.1 (10)	108.5 (6)	112.7 (7)	114.5 (7)	118.6 (7)	125.1 (7)	182.8 (10)
θ [MeV]					1.64 (8)	1.53 (8)	1.47 (7)	1.42 (7)	1.35 (7)	1.30 (7)	1.51 (8)
Y [$\frac{1}{\text{n/(MeV)}^{16/11}}$)]					2.42 (5)	2.92 (6)	3.28 (7)	3.53 (7)	3.94 (8)	4.39 (9)	5.15 (10)

Tab.10a/NUMERICAL TABLES OF MEASURED NEUTRON SPECTRA AFTER STOPPED NEGATIVE PION ABSORPTION IN Ni ISOTOPES. Symbol definitions are as in Tab.9. The absolute error in normalisation is 20%.

E [MeV]	$\theta(E)$ [MeV]	E_u [MeV]	E_l [MeV]	dE [MeV]	^{58}Ni $\frac{dN}{dE(E)}$ [% n/ π]	^{60}Ni $\frac{dN}{dE(E)}$ [% n/ π]	^{62}Ni $\frac{dN}{dE(E)}$ [% n/ π]	^{64}Ni $\frac{dN}{dE(E)}$ [% n/ π]
103.4	9.8	124.7	87.1	37.6	0.23 (9)	0.13 (8)	0.14 (8)	0.09 (8)
77.9	6.4	87.1	70.1	17.0	0.62 (14)	0.51 (12)	0.57 (12)	0.53 (13)
61.1	4.4	70.1	55.7	14.4	1.11 (16)	1.05 (14)	1.03 (14)	0.85 (15)
49.3	3.2	55.7	43.9	11.7	1.14 (18)	0.95 (16)	1.16 (15)	1.15 (17)
38.3	2.2	43.9	34.6	9.3	0.79 (19)	0.82 (17)	1.06 (17)	1.05 (19)
30.6	1.6	34.6	27.3	7.3	1.45 (23)	1.63 (21)	1.39 (20)	1.85 (22)
24.0	1.2	27.3	21.7	5.7	2.32 (30)	2.33 (26)	2.21 (26)	2.83 (28)
19.3	0.9	21.7	17.3	4.4	2.91 (40)	2.89 (36)	3.04 (35)	4.26 (38)
15.3	0.6	17.3	13.8	3.4	4.30 (47)	3.78 (42)	3.48 (41)	5.18 (45)
12.4	0.5	13.8	11.2	2.7	3.89 (58)	4.38 (52)	4.37 (51)	5.66 (56)
9.96	0.36	11.2	9.07	2.09	6.04 (74)	6.00 (67)	6.58 (66)	8.69 (72)
8.19	0.28	9.07	7.43	1.65	7.87 (87)	8.85 (78)	10.6 (8)	13.6 (8)
6.69	0.22	7.43	6.12	1.31	11.3 (10)	14.3 (9)	15.5 (9)	20.6 (10)
5.56	0.18	6.12	5.08	1.04	15.6 (12)	19.6 (11)	23.8 (11)	27.9 (12)
4.61	0.14	5.08	4.24	0.84	18.6 (15)	25.4 (13)	30.9 (13)	36.9 (14)
3.88	0.12	4.24	3.56	0.68	25.3 (18)	34.7 (16)	41.6 (16)	48.1 (17)
3.26	0.09	3.56	3.01	0.55	27.7 (21)	38.3 (19)	47.2 (19)	57.1 (21)
2.77	0.08	3.01	2.56	0.45	29.8 (25)	44.3 (23)	54.0 (23)	65.3 (25)
2.36	0.07	2.56	2.19	0.37	33.4 (31)	47.1 (28)	58.4 (28)	67.8 (30)
2.03	0.06	2.19	1.88	0.31	45.4 (37)	61.8 (34)	74.4 (33)	83.5 (36)
1.74	0.05	1.88	1.62	0.26	41.6 (46)	56.7 (42)	70.9 (42)	77.0 (45)
θ [MeV]					2.3 (2)	2.3 (2)	2.2 (2)	2.4 (2)
γ [n/(MeV $^{10/11}$)]					0.70 (5)	0.98 (7)	1.25 (9)	1.31 (9)

Tab.10b/NUMERICAL TABLES OF MEASURED AND UNFOLDED PROTON SPECTRA AFTER STOPPED NEGATIVE PION ABSORPTION IN Ni ISOTOPES. E is the particle energy, $dE = 2$ MeV. The errors given are statistical only. The absolute error in normalisation is 15%.

E [MeV]	58Ni		60Ni		62Ni		64Ni	
	measured $dN/dE(E)$ [% p/π]	unfolded $dN/dE(E)$ [% p/π]	measured $dN/dE(E)$ [% p/π]	unfolded $dN/dE(E)$ [% p/π]	measured $dN/dE(E)$ [% p/π]	unfolded $dN/dE(E)$ [% p/π]	measured $dN/dE(E)$ [% p/π]	unfolded $dN/dE(E)$ [% p/π]
96.	0.096(10)	0.095(11)	0.079(9)	0.078(10)	0.064(8)	0.063(9)	0.045(7)	0.046(7)
94.	0.096(10)	0.104(11)	0.079(9)	0.086(10)	0.064(8)	0.070(9)	0.045(7)	0.051(8)
92.	0.124(11)	0.115(15)	0.103(10)	0.095(14)	0.083(9)	0.077(11)	0.061(8)	0.056(9)
90.	0.124(11)	0.126(11)	0.103(10)	0.106(10)	0.083(9)	0.085(9)	0.061(8)	0.063(8)
88.	0.124(11)	0.139(19)	0.103(10)	0.117(17)	0.083(9)	0.094(14)	0.061(8)	0.069(11)
86.	0.163(13)	0.153(16)	0.142(12)	0.130(17)	0.114(11)	0.105(14)	0.084(9)	0.077(12)
84.	0.163(13)	0.167(13)	0.142(12)	0.143(12)	0.114(11)	0.116(11)	0.084(9)	0.085(9)
82.	0.207(14)	0.183(28)	0.178(13)	0.158(24)	0.145(12)	0.127(22)	0.105(10)	0.093(16)
80.	0.207(14)	0.200(16)	0.178(13)	0.173(14)	0.145(12)	0.140(13)	0.105(10)	0.102(11)
78.	0.233(15)	0.218(21)	0.194(14)	0.190(14)	0.162(13)	0.153(16)	0.120(11)	0.112(14)
76.	0.228(15)	0.236(17)	0.201(14)	0.207(15)	0.130(11)	0.167(39)	0.123(11)	0.122(11)
74.	0.229(15)	0.256(32)	0.201(14)	0.226(29)	0.169(13)	0.182(19)	0.123(11)	0.133(15)
72.	0.262(16)	0.276(21)	0.238(15)	0.245(17)	0.181(13)	0.198(22)	0.139(12)	0.145(13)
70.	0.283(17)	0.298(23)	0.255(16)	0.266(19)	0.201(14)	0.233(16)	0.149(12)	0.157(15)
68.	0.297(17)	0.320(29)	0.259(16)	0.287(32)	0.228(15)	0.251(18)	0.158(13)	0.169(17)
66.	0.334(18)	0.343(20)	0.281(17)	0.309(33)	0.259(16)	0.251(18)	0.179(13)	0.182(14)
64.	0.360(19)	0.367(20)	0.324(18)	0.333(20)	0.276(17)	0.271(17)	0.191(14)	0.196(15)
62.	0.388(20)	0.392(20)	0.353(19)	0.257(20)	0.306(17)	0.291(23)	0.208(14)	0.210(15)
60.	0.435(21)	0.418(28)	0.391(20)	0.382(22)	0.324(18)	0.312(22)	0.239(15)	0.225(21)
58.		0.445		0.409	0.364(19)	0.334(36)		0.241
56.		0.473		0.436	0.372(19)	0.358(25)		0.257
54.		0.501		0.464	0.392(20)	0.382(24)		0.274
52.		0.531		0.493	0.402(20)	0.406(20)		0.291
50.		0.561		0.524	0.421(21)	0.432(21)		0.309

Tab.10b

48.	0.585(24)	0.593(24)	0.533(23)	0.555(26)	0.435(21)	0.459(28)	0.331(18)	0.327(20)
46.	0.628(25)	0.626(28)	0.596(24)	0.587(31)	0.452(21)	0.487(34)	0.344(19)	0.346(20)
44.	0.645(25)	0.660(25)	0.622(25)	0.621(29)	0.495(22)	0.516(25)	0.358(19)	0.366(19)
42.	0.667(26)	0.697(28)	0.643(25)	0.657(26)	0.525(23)	0.547(25)	0.359(19)	0.386(27)
40.	0.721(27)	0.735(28)	0.692(26)	0.694(32)	0.556(24)	0.579(25)	0.400(20)	0.408(20)
38.	0.758(28)	0.777(28)	0.730(27)	0.734(34)	0.578(24)	0.613(28)	0.419(20)	0.431(20)
36.	0.810(28)	0.823(34)	0.785(28)	0.777(47)	0.599(24)	0.650(36)	0.446(21)	0.455(22)
34.	0.848(29)	0.874(32)	0.780(28)	0.824(29)	0.663(26)	0.689(26)	0.477(22)	0.481(26)
32.	0.899(30)	0.932(34)	0.839(29)	0.877(47)	0.725(27)	0.733(39)	0.497(22)	0.509(26)
30.	0.902(30)	1.00(5)	0.857(29)	0.937(38)	0.746(27)	0.782(28)	0.497(22)	0.541(27)
28.	1.03(3)	1.08(4)	0.937(31)	1.01(3)	0.792(28)	0.838(30)	0.547(23)	0.577(24)
26.	1.10(3)	1.18(4)	1.00(3)	1.09(3)	0.848(29)	0.904(32)	0.569(24)	0.618(25)
24.	1.15(3)	1.31(4)	1.06(3)	1.20(4)	0.924(30)	0.984(42)	0.607(25)	0.668(25)
22.	1.28(4)	1.47(4)	1.15(3)	1.33(4)	0.982(31)	1.09(3)	0.647(25)	0.730(27)
20.	1.42(4)	1.71(4)	1.30(4)	1.51(4)	1.04(3)	1.21(4)	0.727(27)	0.809(31)
18.	1.63(4)	2.04(4)	1.46(4)	1.77(4)	1.19(3)	1.40(4)	0.785(28)	0.914(28)
16.	1.93(4)	2.56(4)	1.67(4)	2.15(4)	1.30(4)	1.66(4)	0.867(29)	1.06(3)
14.	2.30(5)	3.41(8)	1.94(5)	2.75(6)	1.51(4)	2.06(5)	0.968(31)	1.28(4)
12.	3.03(6)	4.93(6)	2.42(5)	3.80(6)	1.80(4)	2.72(6)	1.14(3)	1.62(4)
10.	4.18(7)	7.95(8)	3.25(6)	5.82(8)	2.37(5)	3.90(7)	1.41(4)	2.19(4)
8.		13.65		9.75		5.86		3.14
6.		17.87		14.46		6.99		3.96
4.	9.50(10)	16.74(10)	7.70(9)	14.49(9)	3.95(6)	5.86(6)	2.30(5)	3.62(5)
2.	7.70(9)	17.63(9)	5.90(8)	5.02(8)	2.95(5)	4.33(5)	1.70(4)	1.73(4)

Tab.10c/NUMERICAL TABLES OF MEASURED AND UNFOLDED DEUTERON SPECTRA AFTER STOPPED NEGATIVE PION ABSORPTION IN Ni ISOTOPES. Symbol definitions are as in Tab.10b.

E [MeV]	58Ni		60Ni		62Ni		64Ni	
	measured $dN/dE(E)$ [% d/ π]	unfolded $dN/dE(E)$ [% d/ π]	measured $dN/dE(E)$ [% d/ π]	unfolded $dN/dE(E)$ [% d/ π]	measured $dN/dE(E)$ [% d/ π]	unfolded $dN/dE(E)$ [% d/ π]	measured $dN/dE(E)$ [% d/ π]	unfolded $dN/dE(E)$ [% d/ π]
100.					0.003(1)	0.004(1)		
98.					0.003(1)	0.005(2)		
96.					0.004(1)	0.006(1)		
94.					0.006(1)	0.007(1)		
92.					0.009(1)	0.009(1)		
90.					0.010(1)	0.010(1)		
88.					0.011(1)	0.012(1)		
86.					0.014(1)	0.015(1)		
84.					0.018(1)	0.018(2)		
82.					0.019(1)	0.021(2)		
80.					0.023(2)	0.025(2)		
78.					0.024(2)	0.029(4)		
76.					0.033(2)	0.034(2)		
74.					0.041(2)	0.039(4)		
72.					0.056(2)	0.046(13)		
70.					0.054(2)	0.052(5)		
68.					0.057(2)	0.060(3)		
66.	0.085(9)	0.092(9)	0.071(8)	0.081(8)	0.053(2)	0.068(11)	0.047(7)	0.050(7)
64.	0.091(10)	0.101(10)	0.084(9)	0.090(9)	0.068(3)	0.076(4)	0.051(7)	0.055(7)
62.	0.101(10)	0.111(10)	0.088(9)	0.100(11)	0.086(3)	0.086(6)	0.057(8)	0.062(8)
60.	0.117(11)	0.122(11)	0.104(10)	0.112(10)	0.089(3)	0.096(3)	0.062(8)	0.069(8)
58.	0.117(11)	0.134(14)	0.112(11)	0.124(11)	0.099(3)	0.101(3)	0.065(9)	0.076(10)
56.	0.137(12)	0.147(12)	0.124(11)	0.137(12)	0.107(3)	0.118(5)	0.075(9)	0.085(10)
54.	0.157(13)	0.160(14)	0.153(12)	0.151(17)	0.116(3)	0.130(6)	0.096(10)	0.094(13)
52.	0.171(13)	0.174(15)	0.154(12)	0.166(12)	0.130(4)	0.142(5)	0.098(10)	0.103(10)
50.	0.159(13)	0.198(15)	0.169(13)	0.180(13)	0.137(4)	0.155(8)	0.100(10)	0.113(11)

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48.	0.195(14)	0.202(15)	0.185(14)	0.195(14)	0.149(4)	0.168(6)	0.118(10)	0.122(12)
46.	0.207(14)	0.217(15)	0.206(14)	0.211(17)	0.174(4)	0.182(6)	0.130(11)	0.133(13)
44.	0.203(14)	0.232(19)	0.197(14)	0.226(19)	0.193(4)	0.195(12)	0.124(11)	0.143(14)
42.	0.223(15)	0.247(16)	0.219(15)	0.242(16)	0.193(4)	0.209(5)	0.138(12)	0.154(13)
40.	0.257(16)	0.262(21)	0.243(16)	0.257(16)	0.209(5)	0.224(5)	0.157(13)	0.164(13)
38.	0.249(16)	0.278(18)	0.255(16)	0.273(16)	0.208(5)	0.239(13)	0.158(13)	0.175(13)
36.	0.266(16)	0.294(17)	0.267(16)	0.289(16)	0.239(5)	0.254(7)	0.169(13)	0.186(13)
34.	0.291(17)	0.312(18)	0.281(17)	0.306(17)	0.254(5)	0.269(9)	0.185(14)	0.198(14)
32.	0.301(17)	0.330(17)	0.286(17)	0.323(19)	0.254(5)	0.286(8)	0.193(14)	0.210(14)
30.	0.320(18)	0.350(18)	0.310(18)	0.342(18)	0.283(5)	0.303(10)	0.208(14)	0.223(16)
28.	0.333(18)	0.373(18)	0.313(18)	0.362(21)	0.288(5)	0.322(5)	0.215(15)	0.236(15)
26.	0.345(19)	0.400(20)	0.333(18)	0.385(20)	0.313(6)	0.343(10)	0.228(15)	0.251(16)
24.	0.374(19)	0.432(19)	0.373(19)	0.413(24)	0.309(6)	0.367(13)	0.233(15)	0.269(16)
22.	0.398(20)	0.473(20)	0.378(19)	0.447(19)	0.334(6)	0.395(8)	0.246(16)	0.289(16)
20.	0.427(21)	0.524(21)	0.413(20)	0.490(22)	0.363(6)	0.431(8)	0.260(16)	0.315(17)
18.	0.462(21)	0.591(21)	0.436(21)	0.548(21)	0.392(6)	0.476(11)	0.275(17)	0.347(18)
16.	0.508(23)	0.680(23)	0.474(22)	0.629(22)	0.404(6)	0.534(10)	0.305(17)	0.389(18)
14.	0.554(24)	0.796(24)	0.506(22)	0.742(25)	0.445(7)	0.610(7)	0.331(18)	0.445(19)
12.		0.936		0.904		0.705		0.515
10.		1.04		1.11		0.806		0.590
8.		0.972		1.28		0.845		0.622
6.	0.652(26)	1.30(3)	0.753(27)	1.53(3)	0.540(7)	1.04(1)	0.400(20)	0.789(20)
4.	0.714(27)	3.14(3)	0.764(28)	2.29(3)	0.555(7)	1.87(1)	0.422(21)	1.49(2)

Tab.10d/NUMERICAL TABLES OF MEASURED AND UNFOLDED TRITON SPECTRA AFTER STOPPED NEGATIVE PION ABSORPTION IN Ni ISOTOPES. Symbol definitions are as in Tab.10b.

E [MeV]	58Ni		60Ni		62Ni		64Ni	
	measured dN/dE(E) [% t/ π]	unfolded dN/dE(E) [% t/ π]	measured dN/dE(E) [% t/ π]	unfolded dN/dE(E) [% t/ π]	measured dN/dE(E) [% t/ π]	unfolded dN/dE(E) [% t/ π]	measured dN/dE(E) [% t/ π]	unfolded dN/dE(E) [% t/ π]
86.					0.003(1)	0.004(1)		
84.					0.005(1)	0.004(2)		
82.					0.004(1)	0.005(1)		
80.					0.004(1)	0.005(1)		
78.					0.006(1)	0.006(1)		
76.					0.007(1)	0.007(1)		
74.					0.009(1)	0.008(2)		
72.					0.010(1)	0.009(2)		
70.	0.006(1)	0.011(4)	0.007(1)	0.010(2)	0.006(1)	0.010(3)	0.005(1)	0.008(2)
68.	0.010(1)	0.012(1)	0.009(1)	0.012(2)	0.008(1)	0.012(3)	0.008(1)	0.009(1)
66.	0.016(1)	0.013(4)	0.014(1)	0.013(2)	0.012(1)	0.013(1)	0.012(1)	0.010(3)
64.	0.011(1)	0.015(3)	0.012(1)	0.015(2)	0.014(1)	0.015(1)	0.009(1)	0.011(2)
62.	0.014(1)	0.017(2)	0.017(1)	0.017(2)	0.013(1)	0.017(2)	0.010(1)	0.013(2)
60.	0.021(2)	0.019(4)	0.021(2)	0.020(4)	0.017(1)	0.019(1)	0.016(1)	0.015(3)
58.	0.020(1)	0.021(2)	0.021(2)	0.023(2)	0.016(1)	0.022(3)	0.015(1)	0.017(1)
56.	0.020(1)	0.024(2)	0.023(2)	0.025(2)	0.020(1)	0.024(2)	0.017(1)	0.019(1)
54.	0.021(2)	0.027(3)	0.024(2)	0.029(2)	0.022(2)	0.027(2)	0.018(1)	0.022(2)
52.	0.027(2)	0.030(2)	0.026(2)	0.032(3)	0.026(2)	0.030(2)	0.024(2)	0.025(2)
50.	0.031(2)	0.034(2)	0.031(2)	0.036(2)	0.030(2)	0.034(2)	0.024(2)	0.028(2)
48.	0.036(2)	0.037(3)	0.034(2)	0.040(2)	0.037(2)	0.038(4)	0.028(2)	0.031(2)
46.	0.040(2)	0.042(4)	0.038(2)	0.044(2)	0.036(2)	0.042(2)	0.032(2)	0.035(2)
44.	0.037(2)	0.046(4)	0.040(2)	0.049(4)	0.042(2)	0.047(2)	0.035(2)	0.039(2)
42.	0.044(2)	0.051(2)	0.048(2)	0.054(2)	0.045(2)	0.052(2)	0.039(2)	0.044(2)
40.	0.048(2)	0.057(3)	0.050(2)	0.060(3)	0.054(2)	0.058(5)	0.041(2)	0.049(2)

38.	0.052(2)	0.063(3)	0.060(2)	0.066(4)	0.060(2)	0.064(6)	0.045(2)	0.055(3)
36.	0.057(2)	0.070(4)	0.062(3)	0.072(3)	0.056(2)	0.071(5)	0.049(2)	0.061(4)
34.	0.064(2)	0.077(3)	0.064(3)	0.079(4)	0.063(2)	0.078(4)	0.055(2)	0.067(3)
32.	0.071(3)	0.085(3)	0.069(3)	0.086(5)	0.068(3)	0.086(6)	0.060(2)	0.074(4)
30.	0.083(3)	0.093(6)	0.085(3)	0.094(6)	0.080(3)	0.095(3)	0.075(3)	0.082(7)
28.	0.086(3)	0.102(3)	0.085(3)	0.104(3)	0.098(3)	0.105(12)	0.078(3)	0.090(4)
26.	0.094(3)	0.112(4)	0.097(3)	0.114(5)	0.095(3)	0.116(3)	0.082(3)	0.099(3)
24.	0.098(3)	0.121(3)	0.109(3)	0.126(9)	0.107(3)	0.128(5)	0.086(3)	0.109(4)
22.	0.103(3)	0.132(5)	0.109(3)	0.141(3)	0.110(3)	0.141(4)	0.097(3)	0.120(3)
20.	0.109(3)	0.143(5)	0.118(3)	0.160(4)	0.118(3)	0.157(4)	0.104(3)	0.133(3)
18.	0.123(3)	0.155(5)	0.129(4)	0.185(4)	0.129(4)	0.175(4)	0.109(3)	0.147(4)
16.	0.131(3)	0.170(6)	0.138(4)	0.212(8)	0.131(4)	0.198(11)	0.121(4)	0.165(4)
14.		0.189		0.271		0.228		0.188
12.		0.222		0.349		0.270		0.221
10.		0.292		0.461		0.336		0.278
8.	0.165(4)	0.478(5)	0.255(5)	0.566(7)	0.210(5)	0.448(12)	0.167(4)	0.393(4)
6.	0.214(5)	0.850(5)	0.270(5)	0.720(5)	0.215(5)	0.596(8)	0.193(4)	0.603(4)
4.	0.272(5)	1.60 (1)	0.298(6)	1.17 (1)	0.235(5)	0.845(5)	0.224(5)	1.04 (1)

Tab.10e/NUMERICAL TABLES OF MEASURED AND UNFOLDED ALPHA SPECTRA AFTER STOPPED NEGATIVE PION ABSORPTION IN Ni ISOTOPES. Symbol definitions are as in Tab.10b.

E [MeV]	58Ni		60Ni		62Ni		64Ni	
	measured $dN/dE(E)$ [% a/π]	unfolded $dN/dE(E)$ [% a/π]	measured $dN/dE(E)$ [% a/π]	unfolded $dN/dE(E)$ [% a/π]	measured $dN/dE(E)$ [% a/π]	unfolded $dN/dE(E)$ [% a/π]	measured $dN/dE(E)$ [% a/π]	unfolded $dN/dE(E)$ [% a/π]
28.	0.049(7)	0.114(15)	0.030(5)	0.103(20)	0.029(5)	0.079(12)	0.034(6)	0.075(8)
26.	0.061(8)	0.150(10)	0.047(7)	0.143(7)	0.035(6)	0.106(6)	0.037(6)	0.096(6)
24.	0.065(8)	0.195(14)	0.066(8)	0.195(21)	0.052(7)	0.142(17)	0.045(7)	0.123(10)
22.	0.063(8)	0.255(9)	0.067(8)	0.267(16)	0.051(7)	0.190(12)	0.041(6)	0.158(6)
20.	0.072(8)	0.338(9)	0.071(8)	0.368(10)	0.053(7)	0.257(8)	0.048(7)	0.204(7)
18.	0.082(9)	0.505(10)	0.064(8)	0.568(22)	0.044(7)	0.388(20)	0.056(7)	0.293(8)
16.	0.100(10)	0.807(13)	0.093(10)	0.924(22)	0.066(8)	0.620(18)	0.064(8)	0.444(11)
14.	0.126(11)	1.26 (2)	0.126(11)	1.46 (3)	0.099(10)	0.958(16)	0.083(9)	0.657(11)
12.		1.93		2.23		1.44		0.964
10.	0.250(16)	2.92 (2)	0.325(18)	3.28 (4)	0.228(15)	2.10 (3)	0.147(12)	1.40 (1)
8.	0.348(19)	4.36 (4)	0.374(19)	4.54 (2)	0.246(16)	2.91 (2)	0.188(14)	2.02 (2)
6.	0.460(21)	3.6 (10)	0.167(22)	3.7 (10)	0.309(18)	2.4 (7)	0.232(15)	1.7 (5)
4.	0.479(22)	0.30 (20)	0.483(22)	0.30 (20)	0.330(18)	0.20 (10)	0.248(16)	0.10 (5)

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